EXPERIMENTS IN PHYSICS

FOR

GENERAL LABORATORY CLASSES

SECOND EDITION

BY

NORMAN E. GILBERT, Ph.D.

ASSISTANT PROFESSOR OF PHYSICS

IN DARTMOUTH COLLEGE

17. 8. 29

Contents

LIGHT

APPENDIX

Introduction

Design. This manual is intended to be used in connection with some general textbook of physics and it is assumed that the student using it is taking or has taken a general lecture or recitation course in physics. No attempt is made to discuss general principles or to derive those equations usually found in general textbooks. Principles are briefly stated and the formulae to be used are usually given, but the student is expected to make constant use of his general textbook for discussion of the principles involved in the experiments.

The experiments are designed

(1) To illustrate general principles and to verify important laws of physics;

(2) To familiarize the student with ordinary laboratory apparatus, with the common methods of measurement of physical quantities, and with the use of instruments of precision;

(3) To train him in clear and systematic methods of recording data and computing results, of discussing sources of error and weighing their importance, and of applying precautions in taking measurements.

Accuracy of Measurements and of Results. Several readings should always be taken of each quantity measured, the number depending upon the difficulty of the measurement and the importance of the quantity in the result sought. The mean of such a series of readings is usually nearer the true value than a single reading and the mean is more trustworthy when the individual readings agree among themselves than when they differ widely. It is important to know how closely such a mean may be trusted. When the number of readings is very great the Method of Least Squares gives a means of estimating the

probable limit of error of the mean, but for a small number of readings this is untrustworthy and it is usually sufficient to determine the probable limit of error by simply finding the difference between the mean and that reading which differs from it most widely.

It is important to know, not the actual error in a reading, but the relative magnitude of the error: e. g. an error of one inch in a mile might be neglected while an error of one inch in a foot would be serious. For this reason the probable limit of error is always computed upon 100 units as a base. This will be called for brevity the "per cent error."

When a result depends upon the measurement of several different quantities which are combined as a simple product or quotient the per cent error of the result is the sum of the per cent errors of the several factors: e. g. suppose the true values of two factors are a and b and that errors e' and e'' were made in measurement. Then the product

$$(a \pm e')\,(b \pm e'') = ab \pm ae'' \pm be' \pm e'e''.$$

But $e'e''$ is small and may be neglected, so that the probable limit of error in ab is

$$e = ae'' + be' \qquad \text{or} \qquad \frac{e}{ab} = \frac{e''}{b} + \frac{e'}{a}$$

If these quantities be expressed in hundredths, e/ab is the per cent error of the product while e'/a and e''/b are the per cent errors of the two factors respectively. This demonstration may be extended to any number of factors and it is evident that if a factor appears to the nth power the per cent error of that factor enters the result n times.

When a quantity enters a formula as squared or cubed, or when a measurement presents special difficulties so that the per cent error is large, care must be concentrated upon this measurement and the other quantities entering may often be measured comparatively roughly. In the earlier

experiments an estimate is sometimes given of the relative number of readings desirable, but the student must always judge for himself. When a sum or difference enters a formula as a factor the per cent error of this factor must be computed separately before combining with the others.

The probable limit of error of the result of each experiment should be computed, and the actual error, if known, should lie within this limit. If it does not some systematic error has probably entered the measurements and this should be sought out.

For examples see "Illustrations" under experiments 1 and 2.

Significant Figures. Readings with any instrument should be made to the smallest unit which the instrument is designed to measure. Frequently tenths of the last unit may be estimated. In every case the reading should be recorded exactly as read so that the amount of care used may be seen at a glance: e. g. 100 cms means that the error is probably less than 1 cm, 100.0 cms means that the error is probably less than 0.1 cm, while 100.00 cms means that the error is probably less than 0.01 cm. In any case the assumption is warranted that the last figure may be incorrect. In combining quantities, as in a product or quotient, it is useless to preserve figures beyond the first which is doubtful: e. g. in the illustration the digits printed in heavy faced type are in doubt and only the first of these digits in the product is of any value whatever. The product should be recorded as 66.84.

$$
\begin{array}{r}
31.2\mathbf{2} \\
2.14\mathbf{1} \\
\hline
\mathbf{3122} \\
1248\mathbf{8} \\
312\mathbf{2} \\
624\mathbf{4} \\
\hline
66.8\mathbf{4202}
\end{array}
$$

Note that the position of the decimal point is quite immaterial. The fourth *significant figure* is equally

untrustworthy wherever the point may be. The position of the point should never be considered in determining when figures may be discarded.

General Instructions. (1) The student should provide himself with a set of report sheets and with a note-book, about 8 x 10 inches in size, having firmly bound leaves.

(2) Before beginning measurements read over carefully the instructions and have clearly in mind the general theory and the reason for and importance of each step.

(3) Devise a systematic scheme for recording data, computations, and results. Illustrations are given under the first few experiments. Readings of the same quantity should be arranged in a vertical column for convenience in comparing the readings and in taking the mean. Reserve the right hand page for permanent records and make all computations on the left hand page. Never use loose sheets.

(4) Record the actual readings taken, never making mental corrections for zero error of instrument or for other errors. All readings taken should be recorded except, possibly, preliminary readings taken solely for practice. Never discard a reading without a definite reason for doing so and always record the reason in a note. Very rarely is it allowable to discard a reading simply because it varies widely from the mean, unless the entire set is discarded and a new set taken.

(5) Always compute the per cent error of each observation and the probable limit of error of the result. Decide which measurement limits the accuracy of the result. If the actual error, when known, is greater than the probable limit of error, go over the measurements carefully in search of systematic errors.

(6) Frequently two observers are needed to perform an experiment. In all such cases, if the length of the experiment does not prohibit, separate sets of readings

should be taken, each observer helping the other in turn. In all cases computations should be made independently.

(7) A carefully prepared report of each experiment, written in ink, should be handed to the instructor at the beginning of the exercise next after that at which the experiment is completed. This report should contain the date the experiment was performed; the name of assistant if two persons worked together; the object of the experiment; a diagram of the apparatus; a brief description of the method used if it differed from that described in the text; the data systematically arranged; an outline of the computations (no arithmetical or logarithmic work); a tabulated statement of results; and a complete discussion of the sources of error discovered and of the precautions necessary to avoid or overcome them.

It is not necessary to answer in full upon the report the questions and problems proposed in the "Discussion."

(8) As soon as suitable groups of experiments have been completed the class will meet in small sections for the discussion of these experiments. The "Discussion" in the text is intended as a guide in the preparation for these discussions. As soon as the entire class has completed the group a formal written recitation will be held covering the group.

Experiments in Mechanics

Experiment I

To Measure a Length and to Find the Number of Centimeters in an Inch

Method 1. Let the length to be measured be the distance between two inch marks on a steel scale graduated in British units. Use a similar scale, graduated in metric units, to make the measurement.

Place the scales so that their graduated edges accurately coincide. If there is any space between the edges the reading will depend upon the position of the eye. Verify this fact. This is the "parallax" error which must always be avoided.

Place the scales together at random. Select two marks on the inch scale as far apart as convenient and note the corresponding readings on the centimeter scale. Estimate in each case to tenths of a millimeter. You have now the same distance measured in inches and in centimeters. The ratio of these measurements is the number of centimeters in one inch.

Repeat the measurements eight or ten times. Use different parts of the scales and different distances to eliminate possible errors in graduation. Always place the scales together at random so that your estimate of the fraction shall not be influenced by the estimate previously made. Record readings and results systematically as in the table given below.

Method 2. Place the scales together at random as above. Starting at one end run the eye along the scales until two marks are found which exactly coincide. Record

the readings corresponding to these marks. Starting at the other end find two other marks which coincide and record the readings corresponding to these marks. From these readings find the distance, measured in inches on one scale and in centimeters on the other, between the two pairs of coincident marks and compute the number of centimeters in one inch.

Repeat eight or ten times, using different parts of the scale and different distances, as in Method 1. Record readings and results systematically as in the table given below.

Illustration

METHOD 1

Inch Scale End A	Inch Scale End B	Interval in Inches	Centimeter Scale End A	Centimeter Scale End B	Interval in Cms	Ratio
3	7	4	12.81	2.64	10.17	2.542
3	7	4	11.85	1.69	10.16	2.540
3	6	3	12.54	4.92	7.62	2.540
3	6	3	13.39	5.76	7.63	2.543
					Mean	2.5412

Greatest deviation from the mean = 18 parts in 25400 = 0.07 of 1 per cent.

METHOD 2

Inch Scale End A	Inch Scale End B	Interval in Inches	Centimeter Scale End A	Centimeter Scale End B	Interval in Cms	Ratio
2 12/16	6 11/16	3.9375	13.9	3.9	10.0	2.540
2 2/16	7 2/16	5.0000	15.0	2.3	12.7	2.540
2 12/16	5 15/16	3.1875	12.5	4.4	8.1	2.541
					Mean	2.5403

Greatest deviation from the mean = 7 parts in 25400 = 0.03 of 1 per cent.

Among the individual results is there any apparent relation between the magnitude of the error and the distance used? What error in the ratio corresponds to an error of 0.1 mm in the estimate when the distance is 10 cms? When the distance is 5 cms? Which method appears to give the more consistent results? Which

method gives the smaller maximum variation from the mean?

Discussion:—Is it easier to estimate to tenths of a millimeter or to decide which pair of lines coincide? When the coincidence method can be used is there any great advantage in graduating a scale in very small intervals?

Experiment 2

The Vernier Caliper

In the simplest form of caliper a single mark on the sliding part moves along a scale. When the jaws are closed this mark is opposite the zero of the scale. Thus the reading on the scale opposite this moving mark indicates the distance between the open jaws. The fraction of the last division must be estimated. (Exp. 1, Method 1)

A vernier is an auxiliary scale on the moving slide by means of which a fraction of a scale division may be estimated by the coincidence method. (Exp. 1, Method 2)

Examine the vernier scale carefully. If the main scale is graduated in millimeters notice that 10 divisions of the vernier correspond to 9 millimeters, i. e. each vernier division is 1/10 mm shorter than a division of the main scale. If the zero line of the vernier is placed on any division of the main scale the first line of the vernier falls 1/10 mm short of the first succeeding division of the main scale, the second line of the vernier falls 2/10 mm short of the second succeeding division of the main scale, and so on until the tenth division on the vernier coincides with the ninth succeeding division of the main scale. Thus when the zeio line of the vernier coincides with a division of the main scale the reading is taken directly. If the 1st, 2nd, or the *n*th line of the vernier coincides with a di-

vision of the main scale the zero line is 1/10 mm, 2/10 mm, or n/10 mm beyond a division of the main scale.

To read such a scale record the number of millimeters the zero line of the vernier has passed over. Record as tenths of a millimeter the number of the line on the vernier which coincides with a line on the main scale. The "Least Count" of such a vernier is 1/10 mm. Before beginning measurements set the vernier at random and take readings until the method becomes familiar.

(1) Measure the Volume of a Cylinder.

Press the jaws of the instrument together gently but firmly and take the "Zero Reading." Record as "Zero Error" the amount to be *added* to each reading subsequently taken with the instrument. Notice whether the jaws touch evenly along their entire length.

Measure the length of the cylinder at least four times, noting its position and turning it systematically about 45 degrees between measurements. If the readings do not agree very closely continue measurements until the source of error is found.

Measure the diameter systematically near each end and near the middle, turning the cylinder into four positions, as above, for each set of measurements. Take more readings in case of disagreement. Compute the volume of the cylinder.

(2) Determine the Value of π.

Use the value of the diameter already found. To find the circumference use a strip of thin strong paper. Cut the edge square and wrap the strip firmly round the cylinder. With a fine pencil point draw a line across the strip where the paper first overlaps. Unwrap the paper and measure with a steel scale the distance to the proper edge of this line. Repeat as many times as necessary. Compute the value of π.

Illustration

(1) Cylinder No. 110.

Zero error of caliper = — 0.01 cm.

	Length	Diameter Top	Diameter Middle	Diameter Bottom
	3.69 cms	1.90 cms	1.90 cms	1.905 cms
	3.69 "	1.91 "	1.91 "	1.92 "
	3.69 "	1.90 "	1.915 "	1.92 "
	3.69 "	1.915* "	1.905 "	1.905 "
Mean	3.69 "	1.906 "	1.907 "	1.912 "
Error	—0.01 "	Mean	1.908 cms	
Length	3.68 "	Error	—0.01 "	
		Diameter	1.898 "	

Greatest deviation from mean length = 0.

Greatest deviation from mean diameter = 12 parts in 1900 = ~~0.06~~%. 0.6%

Volume of cylinder = 10.41 cc.

Probable limit of error = 0 + 2 × 0.6% = 1.2% = 0.12 cc.

(2) Cylinder No. 110.

	Circumference
	6.01 cms
	6.02 "
	6.01 "
Mean	6.013 "
Error	—0.01 "
Circumference	6.003 "

$$\pi = \frac{6.003}{1.898} = 3.163$$

Greatest deviation from mean circumference = 7 parts in 6000 = 0.1 %.

The probable limit of error in π = 0.1 % + 0.6 % = 0.7 %.

The actual error = 21 parts in 3142 = 0.7 %.

---

*An extra figure in such a table represents an estimate beyond the least count of the instrument.

Make a careful drawing of a vernier scale on your report and record the reading represented.

What error in your value of the volume would be caused by an error of 1/10 mm in the length? By an error of 1/10 mm in the diameter? How does the fact that the diameter enters twice as a factor affect an error caused by it in the result? What error in your value of π would be caused by an error of 1/10 mm in the circumference? By an error of 1/10 mm in the diameter? Which measurement in each case limits the accuracy of your result?

Discussion:—If a circle were graduated in half degrees how would a vernier be divided to read to minutes?

Experiment 3

The Micrometer or Screw Caliper

Examine the instrument carefully. The screw, attached to the rotating cylinder or "barrel," moves in a nut attached to the solid frame. The scale on the frame corresponds to the pitch of the screw and by it the number of whole turns of the screw may be noted. Fractions of a turn may be noted by the divisions engraved upon the edge of the barrel. Sometimes a vernier is engraved upon the frame by which fractions of these divisions upon the barrel may be accurately read. The pitch of the screw is always a standard one and it may be determined by a rough comparison with a standard scale.

Measure the Volume of a Steel Bicycle Ball.

Use first a caliper graduated in metric units. Determine the pitch of the screw and find the least count of the instrument, always using the vernier if there is one on the frame. Determine the zero reading carefully several times. Notice that a slight difference in the pressure applied to the barrel may distort the instrument so much

as to cause an appreciable difference in the zero reading. Sometimes a ratchet head is provided to insure uniform pressure in setting, but unless this is in perfect condition it is useless. Practice setting gently by the touch until consistent readings are obtained. Record as "Zero Error" the amount to be *added* to subsequent readings with the instrument. The zero error should be determined at frequent intervals as it is liable to change.

Take several, ten or more, readings of the diameter of the bicycle ball. Take the mean, add the zero error, and compute the volume of the ball in cubic centimeters.

Repeat the readings, using the caliper graduated in British units. Measure the diameter in inches and compute the volume in cubic inches.

Record all readings and results systematically and compute the per cent error of the greatest deviation from the mean in each case.

As a check upon your readings find from the two measurements of the diameter the ratio of the two units of length. The error in this ratio should not be greater than the probable limit of error as determined from the readings.

From the two determinations of the volume compute the ratio of the two units of volume. Notice that this ratio is the cube of the ratio of the units of length and that the per cent error is three times the per cent error of the ratio of the units of length.

Compare the magnitude of the least counts of the two instruments. Which should give more accurate readings?

What per cent error in the diameter would correspond to an error of 1/10 mm in measurement? What per cent error in volume would this cause? Explain.

Discussion:—Compare the least counts of the simple steel scale, the vernier caliper, and the micrometer caliper.

The value of the micrometer caliper depends upon the accuracy with which the screw is cut. How is a screw of

accurately uniform pitch obtained? (See Encyclopaedia Britannica under "Screw.")

Experiment 4

The Spherometer

The spherometer is similar in principle to the micrometer caliper. A distance is measured by noting the number of turns of a screw in a nut. Examine the instrument carefully and determine the least count. The scale at the side corresponds to the pitch of the screw and the number of whole turns is read from this. The fraction of a turn is read from the divisions engraved on the disk.

Spherometer scales are numbered in different ways. The simplest rule for reading the instrument is as follows:--Notice whether the screw is rising or falling in the nut when the disk is turned in the direction of increasing numbers. If the screw is rising consider the bottom of the vertical scale the zero. If the screw is falling consider the top of the vertical scale the zero, disregarding, if necessary, the numbers engraved on the scale. If this rule is followed all readings are taken directly, the number of whole turns from the vertical scale, the fraction of a turn from the disk.

(1) **Measure the Thickness of a Thin Piece of Glass.**

Thoroughly clean a piece of plane plate glass and the thin piece whose thickness is to be measured.

Place the spherometer on the plate glass and turn down the screw till the point just touches the glass. In making settings rely upon the touch, holding the instrument very gently to avoid distortion. Take several readings in this way.

Place the piece to be measured under the central point and take several readings as before. Remove the piece and take more readings on the plane glass. Turn the piece

over and measure again. Record readings systematically and find the thickness of the glass. As a check measure the thickness with the micrometer caliper. Which instrument gives the smaller deviations from the mean of the readings?

(2) Find the Radius of Curvature of a Large Sphere, only a Portion of whose Surface is Available, such as the Surface of a Lens.

Place the spherometer on the lens and set the screw as before. The point of the three fixed legs determine a plane which cuts out a small circle on the sphere. The position of the central point marks the pole of this circle, and the amount the screw was raised is the distance of the pole from the plane of the circle. This can be measured. Take several readings on the lens and repeat the zero readings. Place the spherometer on the page of your notebook and gently press the four points into the paper. The distance from the central point to the others is the radius of the small circle. Measure these three distances carefully and compute the radius of curvature of the surface of the lens.

Record all readings and results systematically. On your report derive, with diagram, the formula connecting the radius with the quantities measured.

Change each reading in turn by five per cent and note the per cent error introduced into the result in each case. Explain the reason for the difference noted.

Which measurement limits the accuracy of your result?

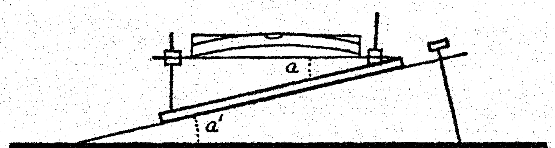
Experiment 5

Use of a Spirit Level

(1) To Adjust the Level.

It is necessary to use a "tester" which consists of a

T-frame resting upon two fixed points and upon the point of a micrometer screw. When the level is properly adjusted the bubble will stand in the center of the glass when the base is horizontal. Place the level on the



tester and adjust the micrometer screw until the bubble is in the center. The tube now makes an angle *a* with the base equal to the angle *a'* which the base makes with the horizontal plane. Turn the level end for end and these angles are added instead of subtracted. Bring back the bubble half way, as nearly as can be estimated, by the micrometer screw on the tester, and half way by the adjusting screw on the level. Turn the level again and repeat until the bubble stays in the center. The two angles represented in the figure are now zero, the level is adjusted, and the tester is level.

(2) To Determine the Sensitiveness of the Level.

The sensitiveness is the number of seconds of arc through which the level turns when the bubble passes over one division.

Measure carefully the pitch of the screw. To do this remove the screw from the nut, lay it on the page of your notebook, and press the threads firmly into the paper. Measure with a steel scale the impression thus made, using the coincidence method if possible. Take several readings. Determine thus the pitch of the screw which is the distance the end of the tester is raised in one revolution of the micrometer head. Compute the number of seconds of arc through which the tester turns when the micrometer head makes one revolution.

NOTE:—Angle (in radians) = arc/radius. $180° = \pi$ radians.

Place the level on the tester and determine the number of revolutions of the micrometer required to make the bubble pass over several divisions. Repeat several times, raising and lowering the end alternately, and using each end of the bubble in turn. Do not allow the screw to wander about the table. Why? Compute the number of seconds through which the level turns when the bubble passes over one division. This is the sensitiveness of the level.

Record all readings and results systematically and find the probable limit of error of your result.

Which measurement limits the accuracy of your result? Explain. Is it necessary that the level be adjusted before the sensitiveness is determined?

Upon what does the sensitiveness of a level depend? Compute the radius of curvature of the tube in your level. Did you find it uniform?

Discussion:—Note that the level may be used for measuring small angles as well as for determining when a surface is level. If the level is not exactly in adjustment how may it be used for measuring such an angle? Should this method always be used? Is exact adjustment ever necessary?

Experiment 6

The Simple Pendulum—To Determine the Acceleration of Gravity

The period of vibration of a simple pendulum depends only upon the length of the pendulum and the acceleration acting. See textbook for theory and derivation of formula.

$$T = 2\pi\sqrt{L/g}$$

where $T =$ the time of one complete vibration, $L =$ the length of the pendulum, and $g =$ the acceleration of

a freely falling body. Since L and T can be measured g may be determined. Solve the equation for g.

Support the pendulum from a clamp so that the thread shall not wind and unwind over the support, thus varying the length, as the pendulum swings. Measure several times the length of the pendulum from the support to the center of the spherical bob. To do this measure to the top of the bob and add the radius of the bob. Let the bob hang freely while measuring. Why?

Start the pendulum with great care. The bob must swing through a very small arc. Why? It must swing in a true plane and must not rotate. Record with stop-watch the time of thirty or more vibrations. Note that the transit at which the watch is started is counted "naught." Count only transits of the thread in one direction. Repeat the determination several times. Compare the stop-watch with the laboratory clock and correct the readings if the watch is not accurate.

If two persons are working together the Method of Passages (See Appendix) may be used advantageously for determining the period.

Substitute the mean values of L and T in the formula and compute the value of g.

Repeat the entire experiment with a widely different length of pendulum.

Illustration

Watch correct.

	Time of 50 vibrations	Time of 1 vibration	Length to top of bob	Diameter of bob
	124.4 secs		151.7 cms	2.54 cms
	124.2 "		151.6 "	2.54 "
	124.0 "		151.5 "	
	124.4 "		151.6 "	
Mean	124.25 "	2.485 secs	151.6 "	2.54 "
	Radius of bob		1.27 "	
	Length of pendulum		152.87 "	

$g = 977.3$

Greatest deviation from mean in measurements of length = 10 parts in 15287 = 0.06%.

Greatest deviation from mean in measurements of time = 15 parts in 12425 = 0.12%.

The probable limit of error is, since the time enters twice as a factor, $0.06\% + 2 \times 0.12\% = 0.30\% = 2.9$ units.

What change in the value of g would be caused by an error of one millimeter in measuring the length? By an error of 1/5 second in measuring the time? Which measurement limits the accuracy of your work? Would it be advantageous to increase the number of vibrations to be timed?

If your watch were gaining 1 second in 10 minutes how would your value of g be affected? Assuming the other measurements correct what rate in the watch would account for your error in g? Notice that a systematic error, such as the rate of the watch, does not appear in the "probable limit of error" unless several watches are used.

Discussion:—Compute the length of a pendulum which would make one complete vibration in two seconds. ("Seconds pendulum.")

Experiment 7

Measurement of Acceleration—Measurement of Time by a Tuning Fork

The acceleration of a body is the rate of increase of its velocity. If the acceleration is constant and if the velocity is known at two moments separated by an interval of time T, then the acceleration is

$$a = \frac{V_2 - V_1}{T}$$

If the velocity is too great to be measured accurately

by a watch, a tuning fork may be used. The period of vibration of a tuning fork is constant, and a wire attached to one of the vibrating prongs of a moving fork may be made to leave a trace on a smoked glass from which the velocity of the fork at any point may be determined.

To determine the acceleration of a falling body let a tuning fork be attached to it. Set the fork in vibration and drop the body in such a way that a stylus on one of the vibrating prongs leaves a trace on a vertical plate of smoked glass.

Beginning with the first well marked waves divide the trace into consecutive groups of five or ten complete waves each, marking the points of division P_1, P_2, etc. Place a meter stick along the trace and record as P_1, P_2, etc., in a column as below, the readings at the points of division of the groups. From these readings find the lengths L_1, L_2, etc., of the consecutive groups and record these lengths in the second column. The mean velocity of the fork while describing each group is $V_1 = L_1/T$, $V_2 = L_2/T$, etc, where T is the time in which the fork described each group. If the acceleration is constant this is the actual velocity at the middle of the corresponding interval. Under these conditions $V_2—V_1$, and therefore $L_2—L_1$, will be the same for all equal intervals, T. The acceleration, i. e. the increase in velocity per second, is then

$$a = \frac{V_2 - V_1}{T} = \frac{L_2 - L_1}{T^2}$$

Find the values of the quantities $L_2—L_1$, $L_3—L_2$, etc., record in the third column, and find the mean. Obtain the period of the fork from an instructor, and compute the value of a only once for each trace. Use at least two good traces, using as many consecutive groups of waves as possible on each trace. Arrange readings and computations as in the following scheme:

P_1		
	L_1 ($= P_2 - P_1$)	
P_2		$L_2 - L_1$
	L_2	
P_3		$L_3 - L_2$
	L_3	
P_4		etc.
	etc.	
etc.		mean

$a =$

Discussion:—Does the initial velocity have any effect upon the subsequent acceleration?

The value of the acceleration is usually less than the value of the acceleration of gravity on account of the friction of the carriage in the guides and of the stylus on the glass and in the smoke. What is the negative acceleration, due to friction, of your falling body? What proportion of the acceleration of gravity is this? This friction may be eliminated by replacing the smoked plate by a photographic plate and the stylus by a tiny mirror reflecting a spot of light upon it. The tuning fork is fixed while the photographic plate is supported by a thread which is burned, allowing the plate to fall freely. The true value of g may be found in this way.

What fraction of a second may be measured accurately by your tuning fork? Under what conditions may a stop-watch be used more advantageously?

The inverse of this method may be used to determine the period of vibration of the tuning fork if the trace is made on a cylinder rotating with known velocity.

Experiment 8

Use of a Balance

To Determine the Number of Grams in a Pound

A balance compares the forces with which the earth attracts two bodies. These forces are the "Weights" of the bodies. Equal "Masses" may be defined as those masses contained in bodies which have equal weights.

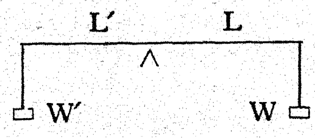
When a balance swings evenly the "moment of the force," i. e. the product of weight and lever arm, on one side equals the moment of the force on the other side. In a good balance the two lever arms are equal, the three knife edges are in the same straight line, there is no friction at the knife edges, and the center of gravity of the beam is just below the central knife edge. For discussion of the general theory see textbook.

Determine the Mass of a Pound, or Other British Unit, in Grams.

Adjust the balances if necessary until they swing evenly. Note the reading of the pointer by taking the mean of two small swings, without waiting for it to come to rest. Place the pound weight in one pan and a large metric weight in the other. If the latter is too large use the smaller weights in order, never using two small weights when an equivalent larger one remains in the box. Use only the weights from a single box. If an exact balance cannot be obtained with the weights given, balance as nearly as possible, then add 1/10 gm and note the amount it moves the pointer. Compute the weight required to bring the pointer to the zero reading. This is practically always necessary.

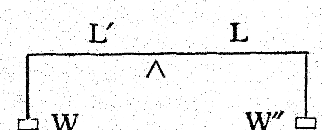
Weigh the pound weight in each pan in turn and take the mean of the two weighings. This eliminates the error due to the difference in length of the two arms of the

scale beam. Since the moment of the force on one side equals the moment of the force on the other side we have



$$LW = L'W'$$

where W is the mass of the pound weight and W′ that of the metric weights in the other pan. Interchanging weights we have



$$L'W = LW''$$

whence $LL'W^2 = LL'W'W''$

and

$$W = \sqrt{W'W''} = \tfrac{1}{2}\,(W' + W'')$$

when W′ is nearly equal to W″. With any balance this will be the case, and this form, being more convenient, should be used.

Remove the weights, take the zero reading again, and repeat the full set of weighings. Take the mean of the two sets. In this way any considerable error due to friction at the bearings may be detected. If disagreements are large take more readings. Never leave the balance until all the weights are properly replaced in the box.

Illustration

Both pans empty, pointer at 5. Zero reckoned at left end of scale.

Mass in lt pan	Mass in rt pan	Pointer	Add 1-10 gm pointer	1-2 lb equals	
226.7 gms	½ lb	4	6	226.75 gms	= W′
½ lb	226.5 gms	5.5	3.4	226.52 "	= W″

Both pans empty, pointer at 4

Mass in lt pan	Mass in rt pan	Pointer	Add 1-10 gm pointer	1-2 lb equals	
226.7 gms	½ lb	1.5	3.5	226.82 gms	= W′
½ lb	226.5 gms	5	3.5	226.57 "	= W″

No. of grams in ½ lb, mean = 226.665

No. of grams in 1 lb = 453.33

Greatest deviation from the mean = 16 parts in 22666 = 0.07%

The change of weight in one pan necessary to move the pointer over one scale division is the "sensitiveness" of the balance. What is the sensitiveness of your balance? Has the balance any device for changing the sensitiveness?

Do your readings indicate any difference in the lengths of the scale beams? What is the apparent ratio of the lengths? How large an error appears to be due to friction in the bearings?

Is the error of your mean value within the probable limit of error which you have computed? Notice that an error in the pound weight or in the metric weights used would appear in all the readings and so would not appear in the computation of the probable limit of error.

Experiment 9

The Analytical Balance

The analytical balance differs from an ordinary balance only in the perfection of its workmanship, particularly at the bearings. The knife edges in an analytical balance are usually of steel or agate and they rest, when in use, upon agate planes. To avoid risk of injury a mechanism is provided for lifting the knife edges off the planes and holding them firmly when not in use.

Caution:—Handle the instrument with the greatest care. Never touch anything on the scale-pan without first raising the beam off the knife edges. Never handle the weights with the fingers.

If the pointer does not stand near the center of the scale when the beam is released call the attention of an instructor.

(1) **To Find the True Zero:**—Set the beam vibrating gently with the pans empty and read five consecutive swings, always reading from the left end of the scale. The odd number of swing is taken because the amplitude of the swing is dying down and so the first and last recorded swings should be taken on the same side. Example:

L	R
6.0	13.2
6.2	12.7
6.4	——
——	12.95
6.20	

$$\text{The true zero} = \frac{6.20 + 12.95}{2} = 9.57$$

Make this determination several times both before and after a weighing and use the mean.

(2) **The Sensitiveness:**—The sensitiveness is the change of weight in one pan, or on one scale-beam, necessary to move the pointer over one division.

Place a small weight in one scale-pan and balance with the rider on the opposite beam. Thus determine the value of the divisions on the scale-beam for this rider. Determine the sensitiveness of the balance.

(3) **Weigh one of the larger weights, e. g. the 10 gram weight, against the smaller weights of the set.**

Always use the rider on the side of the beam with the small weights and use only the numbered divisions of the scale-beam. In weighing never attempt to bring the pointer exactly to the zero, but obtain a reading slightly too small and another slightly too large, find the sensitiveness, and compute the true weight. Always read by vibrations as in finding the true zero.

Weigh the 10 gram weight first in one pan, then in the other, and take the mean of these weights as the true weight. (See Exp. 8)

Illustration

For this rider one of the numbered divisions of the scale-beam corresponds to 0.001 gm.

10 gram weight in Right Pan.

True zero $= 9.57$.

Weights in Left Pan	Rider	Total	Pointer
9.99	7	9.997	8.85
9.99	8	9.998	10.75

$$W' = 9.997 + \frac{.001}{1.90} \times .72 = 9.99738$$

10 gram weight in Left Pan

True zero $= 9.57$

Weights in Right Pan	Rider	Total	Pointer
9.99	7	9.997	10.71
9.99	8	9.998	8.81

$$W'' = 9.997 + \frac{.001}{1.90} \times 1.14 = 9.99760$$

$$\text{Mean} = \overline{9.99749}$$

Inconsistency in weights $= 25$ parts in $100000 = 0.025\%$.

How do your determinations of the sensitiveness agree among themselves? Is there any evidence of a change in its value with the load? How might the load change it? Has the balance any device for changing it?

Discussion:—For the most accurate work a set of weights must be "calibrated." The mass of each weight must be found in terms of the smaller weights of the set and one of the weights must be compared with a standard whose mass is known in terms of the standard kilogram at Paris. Thus the mass of each of the weights in terms of this standard kilogram may be found. Standards of known mass are kept at the Bureau of Standards at Washington and at other national laboratories.

Experiment 10 omit

To Determine the Mass of a Body by the Inertia Method

To compare different quantities of matter some one of the general properties of matter must be taken as the basis of comparison. Thus, two bodies may be defined as having equal "Mass" when the earth attracts them with equal force, i. e., when they have equal weight. Two bodies might equally well be defined as having equal "Mass" when they have equal inertia, and there is no reason for assuming that these two definitions of "Mass" would be consistent. The object of this experiment is to show that they are consistent.

If equal forces act through the same interval of time upon bodies having equal inertia, equal velocities will result. If these velocities can be compared we have a means of comparing the inertia of the two bodies.

Place the two bodies to be compared in two boxes hanging, close together, from threads. Behind the threads support a meter stick in a horizontal position. From another thread hang a spring between the two boxes. Compress the spring and tie with a thread. Place the spring so that, when released, it will act upon the boxes at their centers of gravity. Release the spring by burning the thread. Note carefully the swings of the two boxes. Two observers are necessary.

Since the spring is free to move the two boxes receive equal impulses and therefore equal momenta, i. e. $MV = M'V'$, (Newton's Third Law of Motion). If the masses are equal, the velocities are equal, and equal amounts of kinetic energy are imparted to the boxes. Since there is no friction this kinetic energy will be transformed to potential energy, the boxes will rise equal distances, and in doing so, since they are attached to equal strings, they will swing out equal horizontal distances.

Conversely, if the masses are unequal, they will swing out unequal distances.

Let one of the masses to be compared be a piece of metal and the other be some gram weights. Before releasing the spring record the reading on the meter bar behind each string. Release the spring and record the reading again at the turning point of the swing. The difference gives the amplitude of the swing.

Adjust the gram weights until the two boxes swing equally. Since the boxes themselves may be unequal interchange the gram weights and the unknown mass and adjust again. This will eliminate the difference in the masses of the boxes. The mean of the two determinations should equal the unknown mass. Weigh the unknown mass for verification.

Illustration

Known Mass in Right Can.

Points of Rest Left	Points of Rest Right	Turning Points Left	Turning Points Right	Swings Left	Swings Right	Weights in Right Can	
54.0	46.3	74.0	31.5	20.0	14.8	120	Too Great
53.5	46.6	79.0	27.2	25.5	19.4	100	Too Great
53.0	46.4	76.0	24.5	23.0	21.9	90	Too Great
53.0	46.1	67.0	31.0	14.0	15.1	85	Too Small
53.2	46.2	65.2	24.3	12.0	11.9	88	About Right

Take more readings for verification. Interchange gram weights and unknown mass and proceed as before. Interchange observers occasionally.

Determine from your readings the difference in mass of the two boxes.

Discussion:—Is the mass determined by the inertia the same as that determined by the weight? Which method is the more accurate and which the more convenient for use?

Experiment 11

To Find the Velocity of a Rifle Bullet

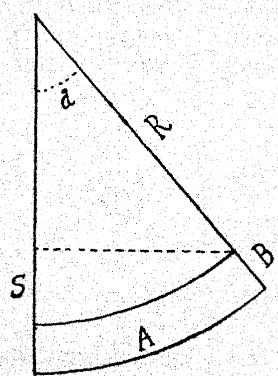
When one moving body strikes another the loss of

momentum of the first equals the gain of momentum of the second. $M'V' = M''V''$, (Newton's Third Law of Motion). When a bullet is fired into a heavy block hanging from a support (ballistic pendulum) the momentum of the bullet is given up to the block. Since the two masses can be found, the velocity of the bullet before impact can be computed if the velocity of the block immediately after impact can be measured.

Weigh a wooden block and attach it in front of the heavy swinging mass. Read on the scale the position of the pointer when the block is at rest. Hold the gun about three feet away and fire a bullet directly into the center of the block in the direction of the swing and note the reading at the turning point of the swing. Fire two or three more shots, cleaning the gun after each shot, and take the mean of the displacements.

Caution:—It is unsafe to try to read the first swing on account of danger from glancing bullets or flying splinters. Read the second and third swing and make a correction, if necessary, to determine the first swing.

The total kinetic energy of the moving mass is used in raising the mass and the height S to which it will rise is independent of the path. Therefore, to find the initial velocity, we may use the formula $V'' = \sqrt{2gS}$ where $S = R - R \cos a = R\,(1 - \cos a)$ and $a = A/(R+B)$.



The velocity of the bullet may be computed from the formula

$$mV' = (M + M' + m)\,V''.$$

where m = mass of bullet,

M = mass of heavy block,

M' = mass of wooden block with bullets previously fired into it,

V' = velocity of the bullet,

V'' = initial velocity of the block.

Obtain from an instructor the mass of the bullets and of the heavy block. Make the other necessary measurements and compute the velocity of the bullet. Record all readings and results systematically.

Discussion:—What error in the result corresponds to an error of 2% in measuring R? An error of 2% in measuring A? Explain both cases. Which measurement limits the accuracy of your results?

What error is introduced if the block is set twisting or swinging sideways?

Experiment 12

A Study of Acceleration by Means of Atwood's Machine

Use of Chronograph for Measuring Time

Atwood's machine consists essentially of two weights attached to a thread passing over a pulley. There are attachments for starting and stopping the weights and for measuring the time they are in motion. By means of this machine velocities much less than those of a freely falling body may be used for studying the laws of falling bodies. (Uniformly Accelerated Motion.)

A chronograph electrically connected to the laboratory clock is used to record intervals of time. Make a drawing of the electrical connections. There are three complete circuits through the battery and chronograph.

Circuit 1 includes the clock pendulum. Each stroke of the pendulum is recorded.

Circuit 2 includes the key and the releasing magnet. Pressing the key starts the falling body and records the instant of starting.

Circuit 3 includes a switch which the falling body strikes at the end of its fall, thus recording the instant of stopping.

The object of the experiment is to verify:

(1) When different forces act upon equal masses the accelerations are proportional to the forces.

(2) When equal forces act upon different masses the accelerations are inversely proportional to the masses.

See textbook for definitions of acceleration, force, dyne, etc.

Theory:—If m' and m'' are the hanging masses the resultant force, i. e. the number of dynes effective in setting the masses in motion, is $m'g-m''g$ dynes and the average number of dynes acting in the direction of motion on each gram of the moving bodies is $\dfrac{m'g-m''g}{m'+m''}$, and this expression, which equals $\dfrac{force}{mass}$, is equal to the acceleration of the moving masses if we neglect friction and the mass of the wheels. If these are included

$$a=\frac{m'g-m''g-f}{m'+m''+k}$$

where $f=$ the friction force and $k=$ the effective mass of the wheels. Eliminate f mechanically by making m' and m'' equal and adding to m' a small weight so that the mass will move uniformly if set in motion downward. For the Wilder Laboratory machine the quantity k is about 10 of the units of mass used.

The object of this experiment is to verify the above expression for the acceleration. We do not measure the acceleration directly but refer to the equation $S=\frac{1}{2}aT^2$, which depends only upon definitions. (See textbook.) If the distance fallen is the same in all cases while a and T vary, we have from this

$$\frac{a}{a'}=\frac{T'^2}{T^2}.$$

Thus we may compare accelerations by comparing the squares of the times required for the body to move over a given distance. The two parts of the expression for the acceleration are verified separately.

(1) **Show that when different forces act upon equal masses the accelerations are proportional to the forces.**

Place 13 units on each side, remembering that the mass of each hanger is 6 units, and adjust the friction weight. Then obtain three records of the time of fall in each of the following cases: when

(A) $m'' = 13$, $m' = 14$, $D = 1$, $T =$ $T^2 =$ $T^2 =$
(B) $m'' = 12.5$, $m' = 14.5$, $D = 2$, $T =$ $T^2 =$ $2T^2 =$
(C) $m'' = 12$, $m' = 15$, $D = 3$, $T =$ $T^2 =$ $3T^2 =$

See that the chronograph was turning uniformly. Measure a space of two seconds (Why an even number?) on several parts of the record and use this as the unit.

In these three cases the total mass is the same while the forces are in the ratio 1 : 2 : 3 and the squares of the times should be in the ratio 3 : 2 : 1, i. e. $T_1^2 = 2T_2^2 = 3T_3^2$.

What is the per cent error of the greatest deviation from the mean?

(2) **Show that when equal forces act upon different masses the accelerations are inversely proportional to the masses.**

Readjust the friction weight with 32 units on each side and obtain three records of each of the following cases: when

(D) $m'' = 31.5$, $m' = 32.5$, $D = 1$, $T =$ $T^2 =$ $T^2 =$
(E) $m'' = 31$, $m' = 33$, $D = 2$, $T =$ $T^2 =$ $2T^2 =$
(F) $m'' = 30.5$, $m' = 33.5$, $D = 3$, $T =$ $T^2 =$ $3T^2 =$

In (1) $m' + m'' + k = 37$ units. In (2) $m' + m'' + k =$ 74 units.

Notice that the forces are equal to those in the corresponding cases in (1) and the total mass is double in each

case. Is the square of the time double? What does this show? What is the per cent error?

Is case (1) verified in the second set of readings? How great is the per cent error?

Discussion:—How would the time of fall be affected if the unit of mass of the weights used should be changed?

How could the value of the effective mass of the wheels be found from your readings?

How could the value of g be found from your readings?

To what accuracy can a time be measured with the chronograph? Compare this method of measuring time with those already used.

Experiment 13

Simple Harmonic Motion—Translation

See textbook for definition and discussion of Simple Harmonic Motion.

The acceleration of a particle moving with S. H. M. is always toward a fixed point and is proportional to the distance of the particle from that point.

Conversely, if the acceleration of a particle moving on a straight line is always toward a point on the line and proportional to the distance of the particle from that point the motion is S. H. M.

Let $a =$ the acceleration of the particle, $x =$ the displacement of the particle from its position of equilibrium, $C =$ a constant depending upon the forces acting, and $T =$ the time of one complete vibration, Then

$$a = Cx \qquad \text{and} \qquad T = 2\,\pi\sqrt{1/C}.$$

(1) Show that the Motion of a Vibrating Spiral Spring Weighted at the End is S. H. M., *i. e.* that the acceleration toward the position of equilibrium is proportional to the displacement.

The acceleration is due to the difference between the

force F exerted by the spring and that mg exerted by gravity upon the weights. When the weight is at rest these forces are equal. Then $F = mg$. By applying different weights we are to show that in general F is proportional to the amount the spring is stretched, i. e. $F = Kx$ where K is a constant equal to the number of dynes required to stretch the spring one centimeter. If K is constant the spring obeys Hooke's law (See textbook) and at each point of equilibrium

$$Kx = mg \qquad \text{or} \qquad K = mg/x$$

Apply an initial weight sufficient to stretch the spring a few centimeters and read the position of the pointer. Add in turn three or four other weights, each sufficient to stretch the spring a few centimeters but taking care not to stretch it too far. Read the pointer in each case. Does the spring obey Hooke's law? Compute the value of K and the per cent error.

(2) Show that the Period of Vibration is

$$T = 2\pi\sqrt{1/C}.$$

A spiral spring without load vibrates as though 1/3 the mass of the spring were placed at the lower end, the spring itself being without weight. Thus if a mass M is hanging on the spring the effective load is $M + m/3$, where $m =$ the mass of the spring. The force at any moment drawing the mass toward its position of equilibrium is $F = Kx$. Since

$$acceleration = \frac{force}{mass}, \qquad a = \frac{K}{M + m/3}\,x,$$

but $a = Cx$ therefore $C = \dfrac{K}{M + m/3}$

and $T = 2\pi\sqrt{\dfrac{M + m/3}{K}}$

This we are to verify.

Use three different masses suitable to the spring used and measure the period of vibration for each case. If two persons are working together the Method of Passages may be used. (See Appendix.) Compute the period in each case by the formula. Is the formula verified? What is the per cent error in each case?

Discussion:—What error in the result is introduced by neglecting the mass of the spring? By using its full value? By a 2% error in the value of K? What is the chief source of error?

Experiment 14

Simple Harmonic Motion—Rotation

This experiment is a continuation of Experiment 13, which should be thoroughly understood before this is undertaken.

The moment of the force required to twist a wire is proportional to the angle through which the wire is twisted. Therefore a twisted wire satisfies the condition for S. H. M., i. e., the angular acceleration toward the position of equilibrium is proportional to the angle through which the wire is twisted. If the wire is clamped at both ends and carries a load at its middle point the acceleration is $a = \frac{2 \pi n r^4}{l I} \theta$ whence, as before, $T = 2 \pi \sqrt{\frac{l I}{2 \pi n r^4}}$ where $l =$ the length of wire, $I =$ the moment of inertia of the load, $r =$ the radius of the wire, and $n =$ the "Coefficient of Rigidity," a constant depending upon the material of the wire.

We shall verify the above relation only in part.

(1) The Period Varies as the Square Root of the Length of the Wire.

Clamp a rod to the middle point of the wire and determine carefully the time of vibration, using three different lengths of wire. Show that

$$T_1 : T_2 : T_3 = \sqrt{l_1} : \sqrt{l_2} : \sqrt{l_3}$$

or $$T_1^2/l_1 = T_2^2/l_2 = T_3^2/l_3.$$

(2) The Period Varies as the Square Root of the Moment of Inertia of the Load.

The last set of readings obtained in (1) may be used as the first set in (2). Keeping the same length of wire change the moment of inertia by placing two cylindrical weights upon the rod about half way between the middle and the end of the rod. Note carefully the distance between the center of the wire and the centers of the weights and make these distances equal. Determine carefully the period of vibration taking care that the weights do not slip. Move the weights to the end of the bar and take a new set of readings. Let

m = mass of the rod alone, m_1 = mass of first weight,
L = length of the rod, L_1 = length of first weight,
R = radius of the rod, R_1 = radius of first weight,
x_1 = distance from center of first weight to center of wire,
I_1 = moment of inertia of the rod alone,
I_2 = moment of inertia of the rod with weights in first position,
m_2, L_2, R_2, x_2, and I_3 have similar meanings.

Then

$$I_1 = m\left[\frac{L^2}{12} + \frac{R^2}{4}\right]$$

$$I_2 = I_1 + m_1\left[x_1^2 + \frac{L_1^2}{12} + \frac{R^2+R_1^2}{4}\right] + m_2\left[x_2^2 + \frac{L_2^2}{12} + \frac{R^2+R_2^2}{4}\right]$$

$$= I_1 + (m_1 + m_2)\left[x_1^2 + \frac{L_1^2}{12} + \frac{R^2+R_1^2}{4}\right]$$

when $x_1 = x_2$, $L_1 = L_2$, and $R_1 = R_2$.

Show that $T_1 : T_2 : T_3 = \sqrt{I_1} : \sqrt{I_2} : \sqrt{I_3}$,

or $$T_1^2 / I_1 = T_2^2 / I_2 = T_3^2 / I_3.$$

(3) **Determine the Coefficient of Rigidity of the Material of the Wire.**

Select one of the sets of readings which give the best agreement in (2) and substitute in the original equation for T after solving it for n. Notice that the radius of the wire appears in the formula raised to the fourth power, hence it must be measured with the greatest care. Use the best micrometer caliper available and measure the wire at different positions, avoiding kinks, dents, etc.

Discussion:—What measurements limit the accuracy of the results in each case?

How would the formula be changed if the load were hung at the end of the wire, only the upper end being clamped? What error is introduced if the load is not at the middle point of the wire?

Given a wire and a body of known moment of inertia, how could the moment of inertia of another body be found?

Have you the data for computing the acceleration when the system is twisted through any given angle? For computing the moment of the force required to hold it there? For computing the force required to hold it there if the point of application is known? The method here suggested is often used to measure small forces (Torsion Balance) as in the experiment of Cavendish for finding the mass of the earth or of Nichols and Hull for measuring the pressure due to radiation.

Experiment 15

Bifilar Suspension

Sometimes, for supporting a vibrating system, it is convenient to use two supports instead of one as in Exp. 14. The two threads should be very flexible, so that their rigidity may be neglected, and they should be exactly parallel when in the position of equilibrium. As the system is twisted about a vertical axis it is raised slightly and a

couple is formed tending to restore it to its position of equilibrium. If set free the system will vibrate and the motion will be Simple Harmonic Motion if the amplitude of vibration is small.

Let L be the length of the suspending threads, D their distance apart, m the mass of the suspended system, I its moment of inertia, and T the period of vibration. Then the acceleration toward the position of equilibrium is

$$a = \frac{mgD^2}{4LI}\theta \text{ and, as before, } T = 2\pi\sqrt{\frac{4LI}{mgD^2}}$$

(1) Moment of Inertia of a Board.

Let the vibrating system be a rectangular board, dimensions a and b, with a circular hole, radius R, cut in the center. Make the necessary measurements and compute the moment of inertia by the above formula.

The moment of inertia of a solid rectangle about an axis at its middle point, perpendicular to its plane, is $M(a^2+b^2)/12$, that of a circle about an axis similarly placed is $MR^2/2$. Compute the moment of inertia of this board to verify the above result. What is the chief source of error in the experiment?

(2) Moment of Inertia of an Irregular Body.

Place the irregular body upon the board used in (1) and find the moment of inertia of the combination, then subtract that of the board already found. If the second body is a disk or rectangle compute its moment of inertia, by the formula given in (1), for verification.

Discussion:—If the moment of inertia of the second body can be computed more easily than that of the board the above process may be reversed. This is frequently done.

The Discussion under Exp. 14 is directly applicable here.

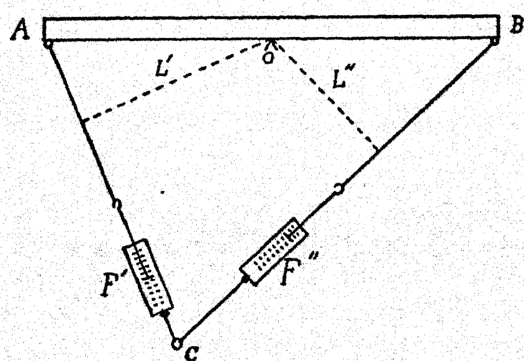
Experiment 16

Law of Moments

The Moment of a force about an axis is the product of the force by its lever arm, i. e. the perpendicular distance from the axis to the line of action of the force.

The object of this experiment is to show that if any number of forces in one plane act upon a rigid body, the sum of the moments of all the forces about any point equals zero when the body is in equilibrium.

Support a bar AB upon a knife-edge O placed at its middle point. Attach cords AC and BC, each containing a spring balance, between the ends of the bar and a screw-eye at C. Draw the strings down till the balances register large forces. Let the forces be F' and F''. Using an L-square and a meter stick measure the lever arms L' and L'' and show that $F'L'=F''L''$. Repeat several times, changing the forces, the position of the screw-eye, and the angle of the bar. Take care that the bar touches the support only at the knife-edge. Record in separate columns the quantities F', F'', L', L'', $F'L'$, $F''L''$, and the per cent error.



Upon your report sheet construct carefully the resultant force acting at C in one case.

Discussion:—Why are moments taken about O rather than about A, B, or C? Does the weight of the bar affect

the experiment? Why? Does the weight of the balances affect the experiment? Why are they placed with the hooks up? What error still remains? Why is it best to use large forces?

Experiment 17

Law of Moments—Parallel Forces - Center of Gravity

The resultant of all the forces exerted by gravity on the particles constituting a body passes through a point called the "Center of Mass" or "Center of Gravity" of the body.

(1) Find the center of gravity of a meter stick by balancing it over a knife-edge. To obtain stable equilibrium the center of gravity of the meter stick must be below the knife-edge. This condition may be realized by attaching a knife-edge to the meter stick and allowing it to rest upon horizontal glass plates like a balance arm. The nearer the center of gravity is to the knife-edge, the more sensitive the balance. Why?

(2) Keeping the fulcrum at the center of gravity balance the stick with unequal weights on the two sides. Verify the law of moments. Make at least three trials.

(3) Place the knife-edge at a distance from the center of gravity and balance the stick by means of a single weight. Compute the weight of the stick by the law of moments. Repeat, using several different positions of the knife-edge. Weigh for verification.

(4) Balance the meter stick using three or more weights and find if the sum of the moments is zero. What is the pressure on the knife-edge in this case?

In every case record systematically as in Exp. 16.

Discussion:—Does the weight of the fulcrum attached to the meter stick affect the results? How should this be adjusted to eliminate the error?

Is it essential that the meter stick should be uniform?

If a large weight near the fulcrum balances a small weight distant from the fulcrum on which side is the error of observation likely to lie? What is the chief source of error in the experiment?

An irregular stick of timber, 20 ft. long, balances over a pivot placed 8 feet from one end. It balances over a pivot placed at the center when a man weighing 150 lbs. sits on the smaller end. Find the weight of the timber.

Experiment 18

Law of Moments—Parallel Forces

If an extended body is in equilibrium under the action of any number of parallel forces in the same plane, then

(1) **The algebraic sum of the forces equals zero.**

(2) **The algebraic sum of the moments about any axis perpendicular to the plane of the forces equals zero.**

Weigh a meter stick and find its center of gravity. Support the meter stick by two threads attached to spring balances. One of the balances should be adjusted in height so that the stick may be placed and kept horizontal. Hang two or more weights, suitable to the capacity of the balances, upon the stick. Level the stick by raising or lowering the adjustable balance. Be sure that all the forces are parallel.

(1) Record in columns the magnitude and the point of application of each force, taking them in order from one end of the rod. Record as + those forces acting upward and as — those acting downward. Add the + forces and the — forces separately and show that the algebraic sum of all the forces equals zero.

(2) Select an axis, perpendicular to the rod, at any point such as one end, the point of application of some force, or a point taken at random. Find the lever arm and

compute the moment of each force about this axis, recording in columns beside those used in (1). Record as + those moments tending to turn the rod counter-clockwise and as — those tending to turn it clockwise. Add the + moments and the — moments separately and show that the algebraic sum of all the moments equals zero.

Choose one or two other axes and verify the second law for each. Rearrange the weights and repeat the experiment. Record the per cent error in each case.

Discussion:—Most of the Discussion under Experiment 17 is directly applicable here.

Show how the weight and the position of the center of gravity of the meter stick might be found from one set of your readings. Note that any two of the quantities recorded might be found if the others are known.

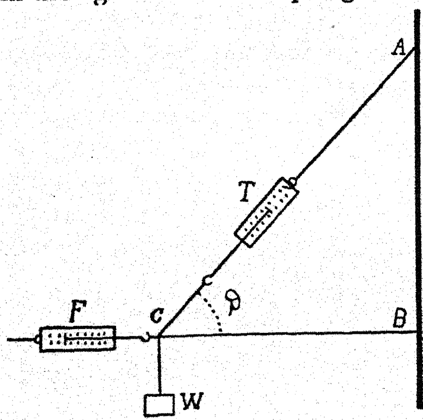
A stick of timber of uniform cross-section is carried by three men, one at one end and two by means of a bar placed crosswise under the stick. Where must the bar be placed that each may carry one-third the weight?

Note:—Two platform balances may be used instead of the two spring balances. Place a knife-edge upon each balance and rest the meter stick upon the knife-edges. All weighings must be corrected for the weight of the knife-edges.

Experiment 19

Forces Acting at a Point—Resolution of Forces—Spring Balance

Support a known mass W against the wall as indicated in the figure. Place a spring balance in AC to record the tension T. BC is a light rod, loose at B, supporting the pressure F. Place a spring balance at C and pull out horizontally until the pressure on BC is relieved and the rod drops. The reading of the balance at that instant is the force F. Show that $F = T \cos \theta$, and $W = T \sin \theta$.



When reading the forces T and F be very careful that the bar to which the hook is attached does not touch the side of the slot. It is well to compare the two balances used by hooking them together and pulling out horizontally. If the readings are not always the same all the forces must be referred to one of the balances taken as standard.

It is difficult to measure AC on account of the spring balance. It is better to measure AB and BC, compute the tangent of the angle, and take the sine and cosine from the tables. Note that the point A is not at the screw-eye but at the point at which the string, produced, would meet the wall. An L-square should be used to keep the rod BC perpendicular to the wall. Record systematically in columns.

Repeat the experiment, using different weights W and different angles θ.

Correction of Balance Reading Due to the Weight of the Hook.

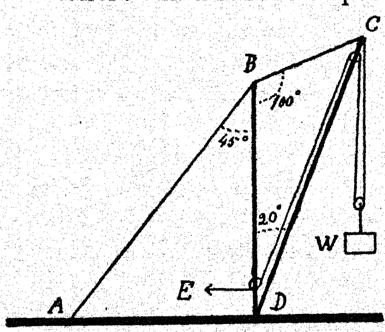
The reading of a spring balance depends upon the position in which the balance is held. If the scale is graduated to read correctly when the balance is held upright, it will read too little, by an amount equal to the mass of the hook plus one-third the mass of the spring, when the balance is in a horizontal position, and by double this amount when the balance is inverted. In intermediate positions the correction is $M(1-\sin\theta)$ where M equals the mass of the hook plus one-third the mass of the spring. M may be found by hanging the balance, inverted, upon another balance, held upright. The difference in the readings is $2M$ for the inverted balance. If the readings are small hang a weight upon the lower balance as the readings of a spring balance may not be accurate when small.

Instead of correcting as above it is usually sufficient to take the zero reading in the position in which the balance is to be used, always tapping the balance to avoid friction errors.

Discussion:—What error is introduced if the mass of the hook is neglected? Why is it better to use large forces? What is the chief source of error?

In what position are the ropes of a hammock when the tension on each equals the weight in the hammock? May the tension on each be greater than the weight in the hammock?

Where will a hammock post, of uniform strength, be most likely to break? Why? If a tall column is to be pulled over where should the rope be attached? Why?



Find the tension in the cable E, the boom CD, the mast BD, the cable BC, and the guy rope AB, of the derrick in the diagram when the mass W = 1000 Kilos.

Experiment 20

Forces Acting at a Point—Force Table

The force table consists of a circular table with the circumference graduated in degrees. Three or more threads, supporting weights, pass over pulleys clamped to the circumference of the table and are attached to a small ring, free to move, over the table.

See that the pulleys run very easily. Adjust the position of the pulleys and the magnitude of the weights until the small ring lies exactly over the center of the table. Angles may then be read directly at the circumference.

(1) **Show that the sum of the components in any one direction, of all the forces acting, is equal to zero.**

Take at random any line through the point of application of the forces and find the component of each force along this line ($C = F \cos a$). Record in columns the magnitude of the forces taken in order, the position of each, the angle a made with the reference line, $\cos a$ (or $\log \cos a$), and $F \cos a$. Is the sum of these components zero? Find the per cent error.

(2) **Show that the sum of the moments of all the forces about any point is zero.**

Take at random any point in the plane and measure the perpendicular distance from this point to the line of action of each of the forces. These are the lever arms of the forces about this point. Compute the moment of each force acting. Record in two more columns in the above table, giving to each moment the sign + or — according as it tends to produce rotation counter-clockwise or clockwise about the axis chosen. Is the sum of these moments equal to zero? Find the per cent error.

Rearrange the weights and pulleys and repeat.

Upon your report sheet draw a diagram of the table with vectors representing the forces used in one case.

(1) Add the vectors geometrically. Since the forces are in equilibrium (i. e. there is no resultant force) the vectors should form a closed polygon. Do they? What is the chief source of error?

(2) The algebraic sum of all the products formed by multiplying each vector by the perpendicular dropped upon it (produced if necessary) from any point in the plane equals zero. Verify.

Experiment 21

A Study of Acceleration—Rolling Motion

The laws of motion for uniform acceleration are

Translation	Rotation
$V = aT$	$\omega = \alpha T$
$S = \frac{1}{2} aT^2$	$\theta = \frac{1}{2} \alpha T^2$
$V^2 = 2\,aS$	$\omega^2 = 2\alpha\theta$

where ω = angular velocity, α = angular acceleration, θ = angular displacement. Then, if R = the radius of the axis,

$$V = R\omega, \qquad S = R\theta \qquad a = R\alpha.$$

When a body rolls it has both translation and rotation but the two may be considered independently.

Use a disk with a small axis resting upon two parallel inclined planes with the disk between. Use a telegraph sounder ticking seconds to measure time. Always use two seconds as the unit since alternate "seconds" may be unequal.

(1) If the Acceleration is Constant the Displacement from rest is Proportional to the Square of the Time.

We may consider translation only since the angular displacement is proportional to the linear displacement. Note the reading at the point at which the disk is to be started. Release the disk upon a tick of the sounder and

record the reading at equal intervals say 4, 8, 12, etc. seconds. Verify the law stated above, i. e. $S/T^2 = \frac{1}{2}a$.

(2) The Angular Acceleration is Proportional to the Moment of the Force acting.

Compute the angular acceleration in case (1) and note the sine of the angle which the plane makes with the table. Using several angles take the necessary data and compute the angular acceleration in each case. Always record the sine of the angle used. The force acting along the inclined plane is $Mg \sin i$ where i is the inclination of the plane. The lever arm is the radius of the axis of the disk. Compute the moment of the force acting and verify the second law stated above.

(3) Moment of Inertia.

The angular acceleration equals the moment of the force divided by the moment of inertia. Express this algebraically, solve for I, and compute the moment of inertia, using some set of data which gives a good result above.

(4) The Kinetic Energy of the Disk at any moment equals the Potential Energy Lost since the time of starting.

$$\tfrac{1}{2}MV^2 + \tfrac{1}{2}I\omega^2 = MgH$$

Select a good set of readings and verify this law.

Discussion:—The sources of error are numerous and some of them are systematic so that very close agreement should not be expected in the last case. Any retardation due to air friction or to irregularity in the disk, axis, or planes would make the apparent moment of inertia too great. Any energy lost in heat decreases the kinetic energy so that the computed value will probably be less than that of the potential energy lost.

The student should make himself thoroughly familiar with the principles involved. How may the moment of inertia be computed from the dimensions of the disk?

Experiment 22

Elastic Bodies—Hooke's Law—Young's Modulus

(1) **Hooke's Law**:—When the stress applied to an elatsic body is not sufficient to produce a permanent distortion, the reaction tending to restore the body to its unstrained condition is proportional to the strain.

Let $F =$ the force applied to stretch an elastic wire and $e =$ the elongation due to this force. Then, within the limits of elasticity, $F/e =$ a constant.

Let one wire support a frame to which one end of a level is pivoted. Let another wire, similar and parallel to the first, support a frame carrying a micrometer screw upon which the other end of the level rests. Adjust the micrometer screw until the bubble is in the center of the level. Apply weights by equal steps of about 500 grams, waiting a moment for the wire to stretch after each weight is applied. Adjust the level and record the micrometer reading at each step. Use five or six steps. Remove the weights step by step recording readings as before. Compute the elongation e for each step. Is the law verified? What is the per cent error?

Repeat the readings and verify the law again, using the other wire.

(2) **Young's Modulus of Elasticity.**

Let $L =$ the length and $R =$ the radius of the wire. Let the "stress" $=$ the force applied per unit area of the cross-section of the wire, and the "strain" $=$ the elongation per unit length of the wire. Then Young's Modulus of Elasticity E is given by

$$E = \frac{stress}{strain} = \frac{F}{\pi R^2} \div \frac{e}{L} = \frac{F}{e} \times \frac{L}{\pi R^2}$$

Compute F/e from the readings in (1). Measure L and R (the latter with great care) and compute E for the

material of the wire used. Note that F should be expressed in dynes.

Discussion:—If an error of one millimeter were made in recording an intermediate reading in (1) would any error result in the final average of e? Why? Note the great value of a set of *consecutive* readings.

Young's Modulus is a constant for any material. It may be defined as the number of dynes required to stretch a wire of unit length and unit area through one centimeter, assuming the limit of elasticity not passed.

Distinguish between "Modulus" of elasticity and "Limit" of elasitcity. Has brass or rubber the greater modulus? Which has the greater limit?

A scale and vernier might be used, instead of the level and micrometer, to measure the elongation.

Experiment 23

Determination of "g"

This experiment is a repetition of the pendulum method of determining "g," using more accurate methods of measuring the period and the length.

The trial pendulum is adjusted until its period is very slightly less (or greater) than that of the standard clock. An electric circuit contains the trial pendulum and the clock pendulum in series with a sounder and battery. The sounder will tick only when the two pendulums make contact with the drops of mercury at the same instant. This occurs when they are vibrating in the same or in opposite phase. Thus the faster pendulum gains one complete period in the time of two "Coincidences."

If the two periods are very nearly the same the sounder will tick several times at each coincidence. Note the time of the first and last tick and take the mean as the time of the true coincidence.

Let $T =$ the period of the trial pendulum,

$t =$ the number of seconds between alternate coincidences,

Then $T = t/(\frac{1}{2}t \pm 1)$ since the clock pendulum makes $\frac{1}{2}t$ complete vibrations in t seconds. Take observations for about one-half hour and record as follows:—

Number of Coincidence	Began	Ended	Mean	t

In the last column record the time between *alternate* coincidences.

Measure with the cathetometer the length of the pendulum. This measurement requires extreme care. First see that the telescope on the cathetometer is level. Notice for what each adjusting screw is used. Set the telescope so that it can be focussed on the top of the pendulum bob and read the scale carefully. At the top the setting should be made on the knife-edge. Repeat the measurement two or three times, always keeping the telescope level.

Measure the diameter of the bob with the vernier calipers carefully. The length of the pendulum "L" is the distance from the knife-edge to the center of the bob.

Compute "g" from the formula

$$T = 2\pi\sqrt{\frac{L + 2r^2/5L}{g}} \qquad \text{where} \qquad L + \frac{2r^2}{5L}$$

is the distance from the knife-edge to the "Center of Oscillation" of the pendulum. The term $2r^2/5L$ is a correction due to the moment of inertia of the bob, r being the radius of the bob.

N. B.—Keep your watch, rings, and other gold or silver articles away from mercury.

Discussion:—Compare Experiment 6. What is now the probable limit of error in the period? In the length? Which limits the accuracy of the result?

If the time of any coincidence is lost leave a blank space and continue the readings. Fill in the probable time of coincidence later. If an error of one minute were made in recording the time of a coincidence, except the first two or the last two, would any error result? Why? Is it necessary to record the intermediate coincidences at all?

Experiment 24

To Find the Efficiency of a Water Motor

The efficiency of a machine is the ratio of the work it does to the work done upon it.

The work done upon this motor is expended upon a Prony brake which is a band applied to the axle. A lever arm is attached to the brake, its end being supported by a spring. When the motor is running the set screw on the brake is tightened until the arm is horizontal. Then the work done by the motor is

$$W = Fx = T \times 2\pi L \times N$$

where T is the tension of the spring in dynes (measured as in Exp. 13), L is the length of the lever arm, and N is the number of turns of the motor in the time of the experiment.

The work done upon the motor is

$$W' = F' x' = mg \times H = m \times gH = V \times P$$

where m is the mass of the water which passes through the motor during the time of the experiment, H is the height of the reservoir from which it has fallen, V is the volume of the water, and P is the pressure upon it at the nozzle of the motor. Since the density of the water is unity, $m = V$ and $gH = P$.

The pressure is measured by a mercury pressure gauge. It equals Dgh where $D = 13.55$ = density of mer-

cury, and $h =$ the height of the surface of the mercury in the tube above that in the flask. This height must be corrected for the height of the motor above the mercury in the flask.

Measure carefully the area of the bottom of one of the large cans. Start the motor gradually with the water discharging into the other can. When the motor is running steadily, gradually tighten the screw in the brake until the arm is horizontal. Keep the brake well oiled. One observer keeps his hand always on the faucet lever. When everything is running steadily he keeps the mercury in the pressure gauge at a predetermined mark such as the lower end of the upper block. The other observer shifts the discharge stream to the other can and at the same time reads the cyclometer. He then watches constantly the position of the lever arm. If any large change takes place the screw must be readjusted. The brake may be constantly steadied by the hand but must be freed often enough to make sure that it remains horizontal. A run should be discarded if the position of the brake arm varies greatly. When the can is nearly full the discharge stream is shifted back to the first can and the cyclometer read at the instant of change. Before allowing the pressure to change the height of the mercury in the flask above the block upon which it rests should be measured for use in correcting h.

Make at least three satisfactory runs, arrange readings and computations systematically, and compute the efficiency, W/W'. For computation it is well to express this algebraically in terms of the quantities actually measured, to collect the constant terms, and to compute their value once for all. The only variables are the number of turns and the depth of the water in the can.

Experiment 25

The Efficiency of a Water Motor at Different Loads

The "Activity" of a machine is the rate at which it does work.

If the Prony brake is removed entirely from the motor used in Experiment 24, the motor would run at a high rate of speed but the energy of the water would be used in heating the water and the motor. Both the efficiency and the activity would be zero. If the brake were clamped so tightly that the motor stopped, the efficiency and the activity would again be zero. At some intermediate speed the efficiency would reach a maximum value and at some other speed, probably, the activity would reach a maximum.

The load on the motor may be changed by changing the position of the upper end of the spring, thus changing the tension on the lever arm. Take several short runs using different tensions upon the spring. Take the duration of the runs so that the activity may be computed. Compute the efficiency and the activity for each run. Note that these computations may be made very simple if the formulas are expressed in their fundamental terms and the value of the constants computed once for all. The only variables are: (1) The distance the spring is stretched, (2) The number of turns, (3) The depth of water in the can, (4) The duration of the run.

Plot a curve using speeds as abscissas and efficiencies as ordinates and another curve on the same diagram using activities as ordinates. Plot a third curve using activities as abscissas and efficiencies as ordinates. These are the "Characteristic Curves" of the machine. From them the behavior of the machine under any conditions can be seen at a glance. Note that for a given activity there are usually two efficiencies. These curves should be furnished by manufacturers to prospective buyers.

Compute the horsepower of your motor when running at maximum activity: at maximum efficiency.

Experiment 26

To Find the Density of a Regular Body—Weight in Vacuo

The Density of a body is the mass per unit volume.

By Archimedes' Principle a body immersed in a fluid is buoyed up by an amount equal to the weight of the fluid displaced. Thus a body in air is buoyed up by an amount equal to the weight of air it displaces and a correction must be made if the true weight is needed. The corrected weight is the weight "in vacuo."

Each detail of this experiment should be performed with the greatest care. Use an aluminum cylinder and handle it with care as the metal is soft and easily dented. Find the volume of the cylinder by the method of Experiment 2, measuring the length with the vernier caliper, and the diameter, carefully and systematically, with the best micrometer caliper available. Obtain a specially calibrated set of weights from an instructor and weigh the cylinder following in detail the method of Experiment 9. Take the temperature T inside the balance case, the barometer reading h, and the temperature t on the barometer case, immediately after weighing the cylinder. Correct the weight for the buoyancy of the air (See below) and compute the density of the aluminum.

To Read the Barometer:—Some barometers have, at the bottom of the tube, a large reservoir containing an ivory point. The surface of the mercury may be adjusted by a screw until it just touches the ivory point which is level with the zero of the scale on the tube. The height of the surface in the tube above that in the reservoir may then be read directly. Set the vernier so that the lower edge (the zero of the vernier) appears to just touch the top

of the curved surface of the mercury. Take the reading h and correct as indicated below.

Some barometers have the mercury in a U-tube with one arm closed. There is a vernier on each arm. Set the verniers as directed above and the difference in the readings is the distance h between the two surfaces. This must be corrected as indicated below.

Both the mercury and the brass scale expand when heated. The first tends to increase the reading, the second to decrease it. If H is the true reading when the barometer is at 0°C,

$$H = h\,\frac{1 + .000018\,t}{1 + .00018\,t} = h\,(1 - .00016\,t) \text{ nearly.}$$

(See Exp. 42.)

Density of Air:—The mass of 1 cc of dry air under standard conditions (Temperature = 0°C, pressure = 76 cms of mercury) is 0.001293 gms. This varies both with the temperature (Exp. 43) and with the pressure (Exp. 35). It is proportional to the pressure and inversely proportional to the absolute temperature, which is obtained by adding 273 to the temperature on the centigrade scale. If H is the corrected barometer reading and T the temperature on the centigrade scale, the density of air is

$$D = 0.001293 \times \frac{H}{76} \times \frac{273}{273 + T}.$$

Weight in Vacuo:—Both the cylinder and the weights are buoyed up by the air, but unequally since they displace, in general, different masses of air. The volume V of the cylinder has been measured, that of the brass weights V' can be computed by dividing the mass by 8.4, the density of brass. The amount to be added to the cylinder to obtain the weight in vacuo, or the true mass, is $D(V - V')$.

Discussion:—What per cent error would have been

made if the weight in air had been used? What value of the density would have been obtained?

The density of gold is 19.3. What would be the correction for a cylinder of gold the size of your aluminum cylinder? What would be the correction for a cylinder of brass the same size?

A table will be found in the Appendix giving the corrections to be made to the barometer for different temperatures. These values are computed by the formula given above. If greater accuracy is needed correction should be made for the capillary depression of the mercury and for variation in "*g*." The former is zero in a U-tube and the latter is usually small. Both may be taken from tables when needed.

Experiment 27

Capacity of a Bulb—Density of a Liquid

Use a "Specific Gravity Bottle," a bottle having a ground glass stopper pierced with a small hole, or a "Pyknometer," a bulb with two capillary stems.

Thoroughly clean the pyknometer by washing with nitric acid to remove soluble dirt, with distilled water, with chromic acid to remove grease, and again with distilled water. Suck small quantities of the washing fluids into the bulb, using a rubber tube to avoid getting acids onto the teeth. Avoid staining the fingers with the acids. Remove the fluids by closing the upper opening with the finger and warming gently over a flame. The vapor pressure will force out the fluid. Do not blow through the bulb. Dry by drawing air through while gently heating the bulb over a flame. The interior of the bulb must remain dry when cooled.

Weigh the pyknometer to the nearest milligram. The other errors make greater care unnecessary. Fill the bulb

completely with distilled water, carefully dry the outside, and weigh again. Avoid pressing or heating the bulb with the hand. Why? Find the mass of water in the bulb, take from the table in the Appendix the density of water at the temperature of that used, and compute the capacity of the bulb at this temperature.

One cubic centimeter of glass expands 0.000026 cc for each degree it is heated between 0°C and 100°C. Compute the capacity of your bulb at 0°C.

Remove the distilled water by sucking or by heating very gently to avoid breaking the glass. Fill the bulb with a salt solution and weigh again. Compute the capacity of the bulb at the temperature used and find the density of the salt solution. If the bottle containing the solution is numbered record the number. In all of the experiments upon the density of liquids use the same solution.

Discussion:—Air dissolved in the water introduces an error into this method of finding the capacity of a bulb. The air may be removed by boiling the water.

The specific gravity bottle may be used for finding the density of small shot or metal turnings. The volume of the metal is found by finding the volume of water displaced. How may this be done accurately?

The density of a liquid at different temperatures may be found by placing the pyknometer, full of the liquid, in baths at different temperatures. After removing from the bath the liquid may contract and not fill the bulb but this introduces no error. The capacity of the bulb must be computed for each temperature used. If the "Coefficient of Expansion" of the liquid is known that of the glass might be determined.

What is the derivation of the word "Pyknometer?"

Experiment 28

Density of a Liquid by Balanced Columns

(1) Liquids Which Do Not Mix.

If a liquid is poured into a U-tube the surfaces in the two arms will be at the same height. If there are different liquids in the two arms the pressure will be the same in both arms at the level of the surface of separation of the liquids. Above this level the two surfaces would stand at heights inversely proportional to the densities of the liquids if there were no capillary action. The effect of capillary action may be eliminated by balancing two short columns, then two longer columns. The *change* in the length of the column on one side balances the *change* on the other side.

Use mercury and water. See that the surfaces of the mercury are clean. Pour a few centimeters of water into one arm. A little water on the mercury in the other arm will help to keep capillary action uniform and will introduce no error. Why? With an L-square take the reading at the surface of separation of the two liquids, the reading at the top of the water column, and the reading at the top of the mercury in the other arm. Find the lengths of the balancing columns. Nearly fill the water arm with water and again find the lengths of the balancing columns. Compute the density of the mercury. Repeat several times.

(2) Liquids Which Mix or React Chemically Upon Each Other.

Use two inverted tubes, connected at the top, and dipping into glasses of the liquids to be compared. If some air is removed from the top of the tubes the liquids will rise in the tubes. Since the difference in pressure between the surface in the tube and that in the glass below is the same in both arms the lengths of the balanced col-

umns would be inversely proportional to the densities if there were no capillary action. This error is eliminated as in Case 1.

Use water and a salt solution. In all of the experiments upon the density of liquids use the same solution. Record the number of that used. Suck the liquids up a short distance into the tubes. Be sure the pinch cock does not leak. If the glasses and tubes are not exactly alike determine the length of the balanced columns. Raise the liquids to a greater height and determine the lengths again. The *change* in the length of one column balances the *change* on the other side. Compute the density of the salt solution. Repeat several times.

If the glasses and tubes are similar it is necessary to determine only the change in the positions of the upper surfaces. Why? This is usually the better plan as it is not easy to read accurately the levels of the liquids in the glasses.

Discussion:—What error in the density would result from an error of 1 mm in reading the position of a surface? What error results from taking the density of water as unity? (See table in Appendix.) Is it worth while to use the exact density of water in your experiment?

What errors would be introduced if the tubes were irregular in cross-section? If the tubes and meter stick were not vertical but parallel? If air bubbles stuck to the side of the mercury tube?

Is the weight of the liquids supported by the stand in Case 2?

Experiment 29

Laws of Fluid Pressure—Archimedes' Principle—Hydrometers

A hollow aluminum cylinder, closed at one end, is

used. Place enough load in the cylinder to cause it to float upright. Let $P =$ the pressure at any point in the liquid, $H =$ the depth, $A =$ the area of the base of the cylinder, $F =$ the force exerted on the base, and $D =$ the density of the liquid. The cylinder is supported entirely by the upward force on the bottom and this equals the product of the pressure and the area, i. e. $F = PA$.

(1) The Pressure is Proportional to the Depth.

Drop shot into the cylinder until one of the marks on the side is level with the surface of the water. This is best tested by looking upward from below the surface. Keep the cylinder wet to avoid irregular capillary action so far as possible. Drop in shot, one by one, until the cylinder sinks several centimeters, counting the number required for each centimeter. Is this number constant? Is the increase in the force required to support the cylinder the same for each centimeter? If $F = PA$ is the increase in pressure constant? Is the law verified? Repeat the experiment using a cylinder of different cross-section.

(2) The Force is Proportional to the Area.

Show that the number of shot required for the two cylinders is proportional to the areas of the bases of the cylinders.

(3) The Pressure at Any Depth Equals DgH.

Weigh the cylinder with the shot contained and compute the pressure on each square centimeter of the base. Is the law verified? Note that if the pressure is expressed in grams it is numerically equal, in water, to the depth expressed in centimeters.

(4) Archimedes' Principle.

Is the weight of the cylinder equal to the weight of the water displaced? From this principle compute the mass of each shot.

(5) Density of a Liquid.

Place the cylinder in a salt solution. In all experi-

ments upon the density of liquids use the same solution. Record the number of that used. Float the cylinder at some line. Weigh the cylinder with the shot contained and compute the pressure on the bottom of the cylinder and so the density of the salt solution from the formula $P = DgH$.

Discussion:—Which cylinder is more sensitive to a change of mass? If the cylinder were replaced by a body of irregular form, should the area at the base or at the surface of the water be used? What form of body would be best for finding the mass of the shot in Case 4? Is the volume of the body under water important? (See Exp. 31.)

When the "Hydrometer" is used for finding the density of a liquid is the volume of the body under the surface important? Why?

Experiment 30

Density of Solids and Liquids

The Density of any substance is the mass of one cubic centimeter of the substance. The mass of the body is found by weighing. The volume of an irregular solid may frequently be best found by Archimedes' Principle.

(1) Density of Brass.

Use the cylinder measured in Experiment 2. If you did not record the number of the cylinder you used determine the volume of another. Weigh the cylinder and compute its density. $D = M/V$.

Suspend the cylinder in a glass of water by a thread from the balance and weigh again. Be sure that no bubbles stick to the brass. The loss of weight gives the weight of the corresponding volume of water. The volume of the water, and thus of the cylinder, can be found by dividing this weight by the density of water at the temperature used. See table in Appendix. Compare the volume

thus determined with that obtained by measuring. Which do you consider more accurate?

(2) Density of a Salt Solution.

Weigh the cylinder in a salt solution. Use the solution you have already used in previous experiments. The loss in weight equals the weight of the corresponding volume of the salt solution. Compute the density of the salt solution.

(3) Density of a Block of Wood.

Weigh the block of wood in air. Fasten a sinker below the block sufficient to submerge it in water. Weigh again with the sinker submerged but with the block in air. Lower the block into the water and weigh again. From the loss of weight compute the true volume of the block and thus the density of the wood.

Discussion:—What error is introduced by taking the density of the water as unity? Is the correction worth making in this experiment?

Given a tin can, a centimeter rule, and a pond of water, how might the density of some pebbles be found?

Discuss the relative accuracy of the methods used for finding the density of the salt solution.

Experiment 31

Density of a Solid by Nicholson's Hydrometer

Nicholson's hydrometer is a sensitive form of the instrument used in Experiment 29. The volume of the instrument is a little more than sufficient to float it. The stem, which passes through the surface of the water, is very small. A pan at the top and a basket below are provided to hold weights or the body whose density is to be determined.

Place weights upon the pan until the hydrometer sinks

to the mark on the stem. Keep the stem wet while testing and do not let the surface film catch in the mark. It is best to view the mark from below the surface when adjusting. Remove the weights and place a small coin on the pan. Add weights until the mark is again at the surface. The weights replaced by the coin equal the mass of the coin. Place the coin in the basket below the surface, taking care not to catch an air bubble under it. Again bring the mark to the surface. The new weights added equal the loss of weight of the coin in water, or the volume of the coin. Compute the density of the coin.

Find the density of a piece of cork.

Experiment 32

Density of a Solid by Joly's Balance

Joly's balance consists of a sensitive spiral spring supporting two light scale-pans, one above the other, connected by a fine wire. The lower pan hangs submerged in a glass of water, the fine wire passing through the surface of the water. See that no air bubbles stick to the submerged pan. Place a coin upon the upper pan and add weights until the pointer sinks to a predetermined mark. Remove the coin and place additional weights upon the pan until the pointer is again at the same mark. The weights which replace the coin equal the mass of the coin. Place the coin in the lower pan taking care not to catch an air bubble under it. Again bring the pointer down to the mark. The new weights added equal the loss of weight of the coin in water or the volume of the coin. Compute the density of the coin.

Find the density of a piece of cork.

Experiment 33

Surface Tension of Liquids

The surface molecules of a liquid behave as though they formed a thin elastic film spread over the surface of the liquid. The force required to break a strip of this apparent film one centimeter wide is the Surface Tension of the liquid.

When a horizontal wire is drawn from below the surface of a liquid a double film covers it and tends to draw it back. The force exerted by such a double film is to be measured.

Use a rectangular frame of aluminum wire hanging from a delicate spiral spring. Determine, as in Experiment 13, the number of dynes required to stretch the spring one centimeter, using 1 gram and 2 grams as the weights. Hang the weights by a thread and correct for the weight of the thread. Be careful to avoid parallax.

Be very careful not to abuse the the spring.

Measure the width L of the aluminum frame between the inside edges of the wires. Clean the frame by dipping it into a solution of caustic potash, then rinse thoroughly under the tap and finally in distilled water. Do not touch the frame with the fingers afterward. Obtain a fresh supply of distilled water for your measurements. Take the reading of the pointer when the frame is about half immersed in the water, i. e. in the position at which the film will break. Immerse the frame entirely and slowly draw away the water. Watch the pointer and take the reading just as the film breaks. All vibrations of the spring must be stopped. Repeat several times. Discard any readings considerably below the average as they are probably caused by jarring. Compute the force F exerted by the two films.

Compute the surface tension of water T from the formula $F = 2LT$.

Measure the surface tension of alcohol.

Discussion:—The surface tension is greatly affected by impurities in the water. Obtain a fresh supply of distilled water just before making the final measurements.

What is the force in grams exerted by the surface tension of water upon the stem of an hydrometer 2 mm in diameter?

See Discussion under Experiment 34.

Experiment 34

Surface Tension of Liquids—Capillary Tubes

When a small tube is dipped into a liquid which wets the material of the tube the liquid rises a certain distance in the tube. The weight of the liquid raised above the surface outside the tube is supported by the force exerted by the surface film at the line along which it is attached to the tube, i. e.

$$\pi r^2 H D g = 2 \pi r T$$

where $r =$ the radius of the tube, $H =$ the height the liquid rises, $D =$ the density of the liquid, and $T =$ the surface tension.

Clean the tube with chromic acid or caustic potash and distilled water. Dry thoroughly. To determine the radius draw into the tube a thread of mercury and measure its length carefully. Avoid touching mercury to your teeth, watch, rings, etc. Weigh the mercury (Density = 13.55) and compute the radius of the tube. Dip the tube into distilled water and thoroughly wet the inside. Measure the height to which the water rises, with a cathetometer if one is available. Compute the surface tension of water.

Measure the surface tension of alcohol. (Density about 0.82.)

Discussion:—See Discussion under Experiment 33.

Discuss sources of error. Which measurement limits the accuracy of the experiment?

Capillary action is a troublesome source of error whenever the height of a liquid in a tube is observed. With mercury the surface is depressed, the surface tension being about 450 dynes. The depression is appreciable in reading the barometer except in the U-tube form. Here the depressing forces in the two arms balance if the tubes have the same diameter. In other cases, whenever possible, a change in height should be used as in Experiment 28.

Experiment 35

Boyle's Law

N. B. Keep mercury away from watches, rings, etc.

Boyle's Law:—The volume of a given mass of gas at constant temperature is inversely proportional to the pressure. i. e. $PV = C$.

The apparatus for verifying the law consists of a glass tube, with a stop-cock at the upper end, connected by a rubber tube to another glass tube which can be raised and lowered. The glass tubes should be about half filled with mercury when they are at the same height. The length L of the air space may be used as the volume ($V = LA$) since the cross-section A of the tube is uniform except for the short space near the stop-cock. The correction for this space is given on the instrument. The pressure at any time upon the enclosed air equals the atmospheric pressure ~~(Corrected barometer reading. See Exp. 26.)~~ plus the excess in height ~~(corrected for temperature)~~ of the surface of mercury in the open tube above that in the closed tube.

(1) Pressures Greater than One Atmosphere.

Open the stop-cock and adjust the tubes until the mercury stands near the base of the tube below the stop-cock.

Close the stop-cock, thus enclosing the mass of air to be used in the experiment.

Using an L-square, read the position of the surface of mercury in each tube. Raise the open tube, step by step, and read the position of both surfaces at each step. Always wait a few moments for the temperature to become constant before reading. If the stop-cock leaks call the attention of an instructor. Use five or six steps in all. Compute the pressure and the volume of the enclosed gas at each step and show that the product is constant.

(2) **Pressures Less than One Atmosphere.**

Lower the open tube, open the stop-cock, raise the surface of the mercury to within a few centimeters of the stop-cock, and again close the stop-cock. Repeat the readings as above, except that the open tube is now lowered instead of raised. Show that PV is a constant.

The constant in this case differs from that above since the mass of air is different. Start the experiment again with the surface near the middle of the tube below the stop-cock and show that the constant is the same above and below one atmosphere.

Discussion:—The pressure has been expressed in centimeters of mercury. Compute the pressure of the atmosphere in grams: in dynes. What is the C. G. S. unit of pressure?

What is the pressure inside a diving suit 100 ft. below the surface of fresh water?

Experiment 36

Density of Air

The density of air may be found by weighing the air contained in a globe of known capacity. Find the exterior volume of the globe by finding the loss of weight of the

globe in water, using a sinker as in Experiment 30. Be sure the stop-cock is closed while weighing in water. The interior capacity is found by subtracting from the exterior volume the volume of the metal, found by dividing the mass of the metal by its density (Copper = about 8.9).

Attach the globe to the pump by a rubber tube and pump out as much air as possible. Pumping should be continued for a few moments after the air appears to be exhausted as the air in the globe, under small pressure, flows out slowly through the stop-cock. Open the stop-cock on the pressure gauge attached to the pump and read the pressure, which is that of the air left in the globe. Call this P'. This stop-cock should be kept closed except when readings are being taken as the vibrating mercury is likely to break the glass.

Let M be the mass of air in the globe before pumping, M' that remaining after pumping. Weigh the globe very carefully with the air exhausted. Admit the air and weigh again. The gain in weight, $(W - W')$ is equal to $(M - M')$, the weight of the air pumped out.

Let P be the pressure before pumping (barometric pressure).

Then $\dfrac{M}{M'} = \dfrac{P}{P'}$ and $\dfrac{M}{M - M'} = \dfrac{P}{P - P'}$

From this equation M can be found and hence the density by the usual formula $D' = M/V$. To reduce to standard conditions (See Exp. 26, "Density of Air"),

$$D = D' \frac{76}{P} \frac{273 + T}{273}.$$

Repeat the two weighings for verification.

Discussion:—What would be the volume of a globe, containing an amount of copper equal to that in yours, which would weigh nothing when empty under standard

conditions? What would be the thickness of the copper shell?

What would be the volume of a balloon weighing 50 lbs. which would just lift a man weighing 150 lbs. when the balloon was filled with hydrogen (density $=$ .000090)? When filled with coal gas (density $=$ .0004)?

Experiments in Sound

Experiment 37

Transverse Vibrations of Strings—Spiral Spring

The period of vibration t of a flexible string, such as a spiral spring or a violin string, is given by the formula $t = 2L\sqrt{m/T}$ and the frequency, the reciprocal of the period, is

$$N = \frac{1}{2L}\sqrt{\frac{T}{m}}$$

where L = the length of a vibrating segment, m = the mass of unit length of the string, and T = the tension in dynes upon the string.

To obtain slow vibrations use a spiral spring supported from the ceiling and stretched by a weight hanging upon it. To prevent swinging the lower end should pass through a small ring or be held loosely in a clamp. Never clamp the spring tightly.

(1) **The Frequency is Inversely Proportional to the Length of the Segment, i. e. NL = C.**

Set the spring vibrating in one segment. Do not grasp it tightly with the hand but merely follow it with one finger. Use only gentle vibrations. Count the number of vibrations of the spring in a given time, say one minute. Repeat several times.

Set the spring vibrating in two segments and count the number of vibrations in the time used above. Repeat with three and with four segments. Is the first law verified?

(2) The Frequency is Proportional to the Square Root of the Tension, i. e. $N / \sqrt{T} = C$.

Note the tension used in case 1. The tension includes the total mass hanging on the spring below the lower node plus one-third the mass of the spring above this node. (See Exp. 13.) The mass of the spring and the distance from the ceiling to the floor are given on the tag attached to the spring. Use another tension differing widely from that above and take the period again with different numbers of segments as above. Is the second law verified?

(3) Velocity of the Impulse.

During one complete vibration the impulse has passed from a given point to one end of the segment, has been reflected at the node, has passed to the other end of the segment, has been again reflected, and has returned to the starting point. Thus the wave has traversed the segment twice in the time of one complete vibration, hence, if λ is the wave-length, $\lambda = 2L$. The velocity of a wave is given by $V = \lambda/t = N\lambda$. Compute the velocity of the impulse in the above cases and show that it is independent of the number of segments but is directly proportional to the square root of the tension.

Discussion:—The above laws assume that the spring is perfectly flexible. This is not the case with a steel spring but the rigidity of the spring increases the velocity of the impulse, thus increasing the frequency.

Note that the frequency would not be changed if the spring were clamped at each node, so that changing the number of segments is equivalent to changing the length of the spring. Vibration with one segment corresponds to the fundamental tone of a piano wire, two segments to the first overtone, or the octave, and so on.

Experiment 38

Transverse Vibration of Strings—Piano Wire

This is the same as Experiment 37 except that the vibrations are too rapid to be counted with a watch. Tuning forks of known period are used instead and, to avoid using an infinite series of forks, the length of the wire is changed by means of a bridge. In this way the wire is tuned to the forks.

(1) The Frequency is Inversely Proportional to the Length, i. e. NL = C.

Use a sonometer with one wire clamped at both ends and one passing over a pulley and supporting a weight. When there is no bridge under the clamped wire its note should be lower than that of the lowest fork. If it is not so ask an instructor to adjust it. Now adjust a bridge under this wire until the note is in unison with the fork. It may be necessary to press the wire against the bridge with the corner of another bridge. If you have not a good ear for music find as nearly as possible the position of the bridge when the beats disappear. Measure the length of the wire and note the frequency of the fork. Tune the wire to another fork by moving the bridge and show that $NL = N'L'$, where N is the frequency and L is the length of the segment of wire used.

(2) The Frequency is Proportional to the Square Root of the Tension, i. e. $N / \sqrt{T} = C$.

Hang about three kilos upon the loose wire and adjust a high bridge under the wire until the note of one portion is higher than that of the clamped wire without its bridge. During the rest of the experiment do not change the length of the portion you are using of the loose wire. Now tune the clamped wire to this portion by adjusting the bridge under the clamped wire. The frequency of the clamped

wire and hence of the portion of the loose wire you are using is now obtained from (1),

$$N' = NL/L'.$$

Hang on some more weights and again find the frequency in the same way. Verify the second law.

(3) **Find the Frequency of an Unknown Fork by Tuning the Clamped Wire to it. N′ = NL / L′.**

Compute the velocity of the wave in the clamped wire.

Note that the tension could be computed if the mass of unit length of the wire were known.

Discussion:—Friction in the pulley causes some error in determining the tension. It is well to tune the wire twice in each case, once after gently lowering the weight upon the wire, again after taking off an excess weight placed on for a moment.

This method is often used to determine the frequency of any periodic motion which can be made to give out a musical note, such as the frequency of an alternating current of electricity.

Experiment 39

Velocity of Sound in Air—Nodes in Organ Pipes

If a vibrating tuning fork is held near the open end of an organ pipe and a plunger is gradually inserted in the other end, at a certain position of the plunger the pipe will respond to the tuning fork or resonance will take place. The air in the pipe is then vibrating in stationary waves, similar to those of a vibrating string, but longitudinal instead of transverse.

If the plunger is moved in further the pipe will respond whenever the plunger arrives at the position of a node of the original vibration. In this way the nodes may

be located. Since a wave passes over two segments in one complete vibration we have

$$\lambda = 2L \qquad \text{and} \qquad V = N\lambda$$

where λ = the wave-length, L = the distance from one node to the next, V = the velocity of the wave, and N = the frequency of the vibration which is the frequency of the tuning fork used. In this way V, the velocity of sound in air, may be determined.

(1) Determine the Velocity of Sound in Air.

As the organ pipe use a vertical tube whose lower end is connected by a rubber tube to a jar of water. By raising and lowering this jar the surface of the water in the tube may be adjusted. Hold the vibrating fork over the tube and locate the lowest node in the tube. Raise and lower the water several times and place a rubber band at the node. In the same way locate the other nodes in the tube. Take the mean distance between the nodes and compute the velocity of sound in air.

Repeat the experiment with another fork of different frequency.

The velocity of sound is directly ~~inversely~~ proportional to the square root of the absolute temp ~~density~~ of the gas. Take the temperature ~~and pressure, find the density of the air in the room (See formula under Exp. 26);~~ and reduce your mean value of the velocity to standard conditions.

(2) Determine the Frequency of an Unknown Fork.

Discussion:—The velocity is affected by the amount of water vapor in the air and by the size of the tube.

There is an anti-node near the open end of the tube. Measure the distance from the upper node to the open end. Is it one-fourth of a wave-lengh? Where is the anti-node?

In making measurements it is well to avoid, when possible, the open ends of tubes.

Experiment 40

Velocity of Sound in Solids—Kundt's Method

The principle of this method is that used in Experiment 39. Sprinkle some fine cork filings along the inside of a long glass tube. On the end of a brass rod fasten a light plunger which fits very loosely inside the glass tube. Insert the plunger in the tube and clamp the rod at its middle point. Stroke the rod longitudinally with a slightly resined cloth until it gives out a shrill note. Adjust the position of the glass tube until the air in the tube responds to this note. The nodes and anti-nodes within the tube will be distinctly indicated by the cork dust.

A longitudinal wave passes to and fro along the brass rod. The middle point, under the clamp, is a node and the ends are anti-nodes. Thus the length of the rod is half the wave-length of the note in brass. The distance between consecutive nodes in the air inside the tube is half the wave-length of the note in air. From this the ratio of the wave-lengths, and hence of the velocities, in brass and in air may be determined. i. e. $V' : V'' = \lambda' : \lambda''$. The velocity of sound in air under standard conditions is known. Compute it for the air in your tube and find the velocity of sound in brass.

Use an iron rod and determine the velocity of sound in iron.

Discussion:—An error is introduced by the heating of the rod as it is rubbed.

A tightly fitting plunger may be placed in the distant end of the tube, making of it a closed pipe instead of an open pipe. In this form the tube may be filled with different gases and the velocity of sound in these gases may be determined.

Experiments in Heat

Experiment 41

Calibration of a Thermometer

It is always essential that the two reference points of a thermometer should be tested before the thermometer is used for accurate work. These reference points are the melting point of ice and the boiling point of pure water under standard pressure. On the centigrade scale these points are 0° and 100° respectively. After testing a thermometer record its number and use it in your subsequent experiments in heat, correcting the readings when necessary.

Test the Zero Point by Melting Ice.

Fill a large breaker or calorimeter with finely broken ice and water or with clean snow thoroughly soaked with water. Place the bulb of the thermometer in the mixture, never allowing it to come near the walls of the vessel. Watch the mercury until it comes to rest and take the reading. Call it *Z*. Allow the mercury to rise again and repeat two or three times. In reading a thermometer great care is necessary to avoid parallax. If the graduations are upon the glass stem stand with your back to the light and slowly turn the thermometer until the reflection of the graduations on the glass can be seen on the mercury column. When reading the thermometer the reflections should always coincide with the lines themselves. Repeat the zero test after the boiling point has been tested.

(2) Test the 100° Point by Steam.

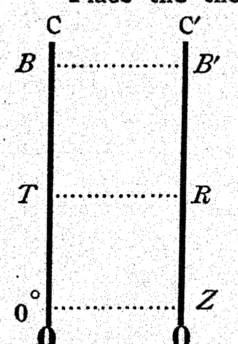
The boiling point of water is affected by impurities

and by the surface of the vessel containing the water. The temperature of the steam over the boiling water is not so affected. It is, however, affected by the barometric pressure inside the vessel. Near the standard pressure the temperature of the boiling water and of the steam over it increases about 1° C for each increase of 26.8 mms of mercury in the pressure.

Use a vessel with a tall tightly fitting cover. Insert the thermometer through a cork at the top. The 100° mark should remain just above the cork and the bulb should be above the water inside. To an opening at the side of the vessel attach a small U-tube containing water to register the excess pressure inside. Leave a small opening at the top for the steam to escape. Boil the water freely and wait for the mercury to come to rest. Call the reading B'. Note the excess pressure inside as indicated by the water in the U-tube. Read the barometer, make the usual corrections, and add the excess pressure to find the pressure inside. Compute the true boiling point, i. e. the temperature of the steam in which the thermometer is immersed. Call this B.

(3) To Correct a Thermometer Reading.

Place the thermometer in some water and take the reading R. The problem is to find T, the corresponding reading on a correctly graduated centigrade thermometer. Let C represent the correct thermometer, and C′ the thermometer used. Corresponding readings are indicated on the horizontal lines. It is evident that



$$\frac{T}{B} = \frac{R-Z}{B'-Z}$$

As an example let the true boil-

ing point be 99.8°, the boiling point as read be 100.1°, the freezing point as read be—.1°, and the temperature of the water as read be 40°. Then the true temperature T is found from the relation

$$\frac{T}{99.8} = \frac{40 + .1}{100.1 + .1}$$

Discussion:—At standard pressure the freezing point of a Fahrenheit thermometer reads 32°, the boiling point 212°. If the temperature of a room is 72° what is the corresponding centigrade temperature? Use the formula given above.

How much does an ordinary change in the barometric pressure affect the freezing point?

The barometer on a mountain reads 60 cms. At what temperature does water boil there? What is the temperature inside a boiler if the excess pressure is 100 lbs. per square inch?

For extreme accuracy it is necessary to correct a thermometer for irregularities in the graduations, irregularities in the bore of the stem, and for other errors.

Experiment 42

Linear Expansion with Heat

The "Coefficient of Linear Expansion" of a solid is the change in length of one centimeter of that solid when heated one degree centigrade. For most solids this is nearly constant for ordinary temperatures. If the length of a rod is L_0 at 0°C and L_T at T°C the coefficient of expansion is

$$a = \frac{L_T - L_0}{L_0 T}, \quad \text{whence} \quad L_T = L_0\,(1 + aT).$$

Place a rod in a long box or jacket with the ends projecting slightly through corks. Let one end of the rod rest

against a fixed metal point. Let a micrometer screw carry a point which may be pressed against the other end. Connect a battery and an electric bell to the two points so that the circuit may be completed through the rod.

Calibrate the micrometer screw as in Experiment 5. Clean the ends of the rod and the metal points. Pass steam from the steam pipes through the jacket until the expansion stops. Press the rod firmly against the fixed point and bring up the point on the micrometer until the bell rings. Repeat several times. Take the reading of the micrometer. Take the temperature of the rod by thermometers inserted through the cover and resting upon the rod.

Pack the rod in clean snow thoroughly soaked in water. The temperature is now 0°C. Set the micrometer again and record the reading. Measure the length of the rod as accurately as possible with a meter stick and compute the coefficient of expansion.

Discussion:—Compute the error in each measurement in turn which would give the error in your result, assuming each time the other two measurements to be correct. Which error is most probable? Where must special precaution be taken?

What per cent error is made in using at 20°C a steel meter scale correct at 0°C (Coefficient of expansion = .000013)?

A steel cube measures 1 cm on each edge at 0° C. What is the volume at 20° C? What is the "Coefficient of Cubical Expansion" of steel? Is it three times the linear coefficient?

Examine the temperature correction applied to the barometer in Experiment 26 and explain the formula.

Experiment 43

Coefficient of Expansion of Air—Absolute Zero

The apparatus used is similar to that used in Experiment 35 to verify Boyle's law. The closed tube is replaced by a bulb which can be immersed in ice and in steam. As the gas expands the pressure might be kept constant, the increase in volume noted, and the coefficient of expansion computed as in Experiment 42. But it is more convenient to increase the pressure and keep the volume constant. Since, by Boyle's law, the pressure varies inversely as the volume the coefficient of expansion is the same at constant volume as at constant pressure. The pressures are measured as in Experiment 35.

If β is the coefficient of expansion of air we have as in Experiment 42,

(Pressure Constant) (Volume Constant)

$$\beta = \frac{V_T - V_o}{V_o T} \quad \text{or} \quad \beta = \frac{P_T - P_o}{P_o T}$$

whence $$P_T = P_o(1 + \beta T)$$

The student should verify and thoroughly understand the relations between these formulas.

(1) Find the Coefficient of Expansion of Air.

Place the bulb in snow thoroughly soaked with water. Use a large battery jar. Bring the surface of the mercury to the ivory point in the stem and record the pressure at 0° C, i. e. P_o. Immerse the bulb in steam over boiling water. Use a large calorimeter with a suitable cover. Compute the temperature of the boiling water as in Experiment 41. Record the pressure at this temperature, i. e. P_T. Before allowing the bulb to cool lower the mercury to prevent its flowing over into the bulb. Compute the coefficient of expansion.

This result is the apparent coefficient of expansion for air in glass. The glass has also expanded. To obtain

the absolute coefficient of air add 0.000026, the coefficient of glass.

(2) **The Air Thermometer.**

The coefficient of expansion of all "permanent" gases is the same (Charles' Law) and equals 1/273 at 0° C. Substituting this in the formula above we have for constant volume

$$\frac{P_T}{P_0} = \frac{273+T}{273}$$

i. e. The pressure of any gas is proportional to its temperature reckoned in centigrade degrees from a point 273 degrees below the freezing point. This point is called the "Absolute" zero, and temperatures reckoned from it "Absolute" temperatures.

Immerse the bulb in warm water, read the pressure, and compute the absolute temperature, and hence the centigrade temperature, of the water. Does this agree with that read on the mercury thermometer?

Discussion:—Using the known value of β we may derive the relations

$V_T/V_0 = (273 + T)/273$ at constant pressure,

and $D_T/D_0 = 273/(273 + T)$ at constant pressure.

The last expression has already been used in Experiments 26, 36, and 39.

The laws of Boyle and Charles may be combined in the single expression $PV = RT$, where R is a constant for a given mass of a gas and T is the absolute temperature.

Experiment 44

Heat Transfer—Water Equivalent of a Calorimeter

The C. G. S. unit of heat, the "Calorie," is the quantity of heat energy required to raise the temperature of one

gram of water one degree centigrade. Quantities of heat are usually measured by determining the amount they will increase the temperature of a known mass of water.

In every experiment involving a transfer of heat, from one body to another the fundamental equation of the heat transfer should be written in the form

$$(\textit{Heat Gained}) = (\textit{Heat Lost}).$$

This equation may then be solved for the quantity to be determined.

All experiments involving heat transfer should be performed as quickly as possible to avoid gain or loss of heat by radiation. To reduce this error as far as possible the calorimeter should be brightly polished and should be placed inside another polished vessel. The intervening space should be closed by a collar to prevent air currents. Methods of correcting for radiation will be described in Experiments 46 and 47.

Water Equivalent of the Calorimeter.

Part of the heat transferred to the known mass of water goes to the vessel containing the water. The heat capacity of this vessel, including the stirrer, thermometer, and other permanent contents, must be determined by a preliminary experiment. This heat capacity is expressed in terms of grams of water and the "Water Equivalent" of the calorimeter is the number of grams of water which would absorb the same quantity of heat, for a given temperature change, that the calorimeter absorbs. More briefly the water equivalent is the number of calories of heat energy required to raise the temperature of the calorimeter one degree centigrade.

There are several slightly different methods of finding the water equivalent.

(1) Weigh the inner calorimeter. Fill it with hot water. Have ready a small quantity of cold water. Take

the temperature of both masses of water. Throw the hot water from the calorimeter as quickly and thoroughly as possible and instantly pour in the cold water, swash it round to absorb the heat from the metal, and take the temperature. Weigh again to obtain the mass of water used. Let $W_0 =$ the mass of cold water used, $w =$ the water equivalent, $T =$ the temperature of the hot calorimeter, $T_0 =$ the temperature of the cold water, and $t =$ the temperature of the mixture. Then the equation of the heat transfer is

$$W_0 (t - T_0) = w (T - t).$$

Solve for the water equivalent.

Success by this method depends upon throwing out all the hot water and throwing in the cold before the metal has lost heat by radiation.

(2) Vary Method 1 by pouring a small quantity of hot water into a cold calorimeter. Write out the equation representing the heat transfer and solve for w.

(3) Vary Method 1 by using a small quantity of hot water (about one-half inch in the calorimeter) and pouring a similar amount of cold water into this. The equation of the heat transfer is now

$$W_0 (t - T_0) = (W + w) (T - t).$$

(4) Vary Method 3 by pouring the hot water into a calorimeter containing cold water. Write out the equation representing the heat transfer and solve for w.

(5) Weigh the calorimeter and stirrer and multiply the mass by the "specific heat" of the metal, i. e. by the number of calories required to heat one gram of the metal one degree. The specific heat of copper is .093. The nickel plate is so thin that the error due to this may be neglected.

Discussion:—The most important errors are those due to radiation and to incorrect temperature readings. In Method 1 the radiation error is probably the largest. It

is decreased by rapidity of manipulation. This error is smaller if some water is used as in Methods 3 and 4 but here the water equivalent is involved in a mass of water and a small per cent error in $(W+w)$ may mean a large error in w. For this reason the mass of water should be kept small. Always avoid small changes of temperature on account of the difficulty of determining them accurately, e. g. use small quantities of water in Methods 1 and 2. Method 5 gives a result usually too large because the lip of the calorimeter, handle of stirrer, etc., do not change temperature as much as the water, though copper is a good conductor of heat and is used in calorimeters for that reason.

Examine your results carefully, repeat in case of inconsistency, and decide which method you prefer and why you prefer it.

Experiment 45

Specific Heat of a Solid

The Specific Heat of a substance is the number of calories of heat energy required to heat one gram of the substance one degree.

Have the material in small pieces so that it will transfer heat quickly. Heat a mass M of the material in a vessel placed in steam or boiling water. Stir thoroughly and when the temperature T is constant throw the material quickly into a known mass W_0 of cold water at temperature T_0. Stir quickly and thoroughly and take the temperature t of the mixture. Do not use the thermometer as a stirrer. If w is the water equivalent of the calorimeter and S the specific heat of the solid the equation of the heat transfer is

$$(W_0+w)\ (t-T_0)=SM\,(T-t)$$

Solve for S and compute the specific heat of the material.

Vary the experiment by pouring the cold solid into hot water and again by pouring hot water into the calorimeter containing the cold solid. In each case only enough water should be used to safely cover the solid. In the last case the amount may be determined after the mixture is made. Always have the material dry. Write out the equation representing the heat transfer in each case and solve for S.

Use the precautions outlined in Experiment 44 and see "Discussion" under the same experiment.

Experiment 46

Latent Heat of Water

The Latent Heat of water is the number of calories of heat energy required to change one gram of ice at 0° C to one gram of water at 0° C.

A known mass M of ice is thrown into a known mass W of warm water at temperature T contained in a calorimeter of water equivalent w. The ice is melted, each gram absorbing L calories, and then heated to the final temperature, t. The equation of the heat transfer is

$$ML+Mt=(W+w)(T-t).$$

Use a stirrer covered with wire gauze to hold the ice below the surface. Break the ice into small pieces. Use a calorimeter about half full of water at about 60° or 70° C. Weigh the water and take the temperature just before putting in the ice. Keep the calorimeter covered. Dry the ice with a towel and put in enough to bring the temperature down to about 10° C. The amount required may be roughly computed and weighed out beforehand. Keep the water stirred until the ice is all melted and take the final temperature. Weigh again to determine the amount of ice used. Compute the latent heat of water. Make two or three determinations.

Discussion:—See "Discussion" under Experiment 44.

Radiation is partly eliminated in this experiment by starting with a temperature above that of the room and ending with one below that of the room. If the temperature fell at a uniform rate the radiation might be almost exactly compensated by starting at a temperature as many degrees above that of the room as the final temperature is to be below. But since the ice melts much more rapidly at the higher temperatures the rate of fall is greater and a higher initial temperature should be used. Again, since the amount of ice used is comparatively small, it is well to use a still higher initial temperature, thus sacrificing something to radiation in order to decrease the per cent errors in determining the amount of ice used and the change in temperature.

The ice should be thoroughly dry and not below 0° C.

Experiment 47

Latent Heat of Steam

If a mass M of dry steam is condensed in a mass W_0 of cold water the equation of the heat transfer is

$$(W_0 + w)\ (t - T_0) = ML + M\,(T - t)$$

The length of time occupied by this experiment will be several minutes and it is necessary to correct carefully for radiation. Determine the water equivalent and the mass of cold water. Start with water as cold as can be conveniently obtained. Have the water in the boiler boiling freely, the steam tube connected to the boiler, and the steam passing through a trap to catch condensed water.

Just before beginning the run determine the rate of radiation of heat into the cold water by keeping the water stirred and taking the temperature each minute for three or four minutes. This gives the rate at the mean of the temperatures used.

When everything is ready record the temperature of the water, empty the trap, and turn the steam into the calorimeter, taking care that the tube dips below the surface of the water. Note the time. Keep the water stirred until the temperature rises 30 or 40 degrees. Remove the steam tube, keep the water stirred, and note the highest temperature reached and the time at which it is reached.

As soon as the cooling becomes uniform determine the rate of radiation as before. From these data compute the rate at the beginning and at the end of the run and the mean during the run. Multiply this by the time of the run and add the correction to the increase of temperature obtained. Compute the latent heat of steam.

Discussion:—The above correction for radiation assumes that the radiation is proportional to the difference in temperature between the inner and outer calorimeters and that the rate of increase of temperature is constant. Both conditions are very nearly satisfied.

It is difficult to get the steam entering the calorimeter dry and to avoid radiation from the flame and boiler to the calorimeter.

Experiment 48

The Mechanical Equivalent of Heat—Joule's Method

In Joule's experiment a measured quantity of mechanical work is expended in friction and the amount of heat generated is measured. The ratio of mechanical work to heat is the mechanical equivalent of heat. The energy is supplied by an electric motor and is transformed into heat by the friction between two brass cones which rub together. The mechanical energy expended in friction is (See Exp. 24)

$$W = \textit{Force} \times \textit{Distance} = F \times 2\pi r \times N.$$

The heat generated is (notation as in previous experiments)

$$H = (W_0 + w)(t - T_0).$$

The water equivalent is comparatively laige and must be computed very carefully.

Brass--Specific heat = .09. Wipe the cones and stirrer dry of oil and water. Weigh and compute the water equivalent of the brass.

Oil—Specific heat = .5. Thoroughly oil the rubbing surfaces of the cones and weigh again. Compute the water equivalent of the oil.

Thermometer:—Glass--Density = 2.6, Specific heat = .16. Mercury—Density = 13.5, Specific heat = .0334. Estimate the volume of each to be submerged and compute the water equivalent.

Fill the inner calorimeter three-fourths full of cold water and find its mass.

Three observers are necessary to take the readings. When everything is ready call an instructor to assist. The machine is run a few moments, till the balance becomes steady, to soften the oil. Then it is stopped and the cyclometer reading and the rate of change of temperature are taken. (See Exp. 47.)

At the final start loosen the inner cone with a screw driver and let it fall gently into place. One observer keeps the water stirred, watches the thermometer, and reads the cyclometer every minute. The second observer reads the balance every ten seconds. If any violent change occurs the run is stopped. The third observer records the time of start, the temperature, and the readings as given by the other observers, and stops the motor instantly if any accident occurs. An increase in temperature of 20 degrees is sufficient for a run.

When the motor is stopped record the highest reading of the thermometer and the time at which it occurs. Then

note the rate of cooling again. Find the average rate of cooling during the run and correct the temperature increase as in Experiment 47. Compute the amount of heat generated. Make a separate computation for the work done in each minute and take the sum as the total work.

Compute the mechanical equivalent of heat, $J = W/H$.

Discussion:—If the speed of the motor were constant the average value of the force during the run might be used or if the force were kept constant, as in Experiment 24, the total number of turns might be used directly in the computation of the work done. But the speed of the motor increases somewhat as the force decreases so that it is necessary to compute independently the work done within the short intervals during which conditions remain comparatively constant. Some error still remains.

Radiation errors may be large and irregular.

Experiments in Electricity and Magnetism

Experiment 49

Lines of Flow and Equipotential Surfaces in a Current Sheet

The Lines of Flow of an electric current entering a sheet of conducting material at one point and emerging at another are similar to those of a current of water entering a pool at one point and emerging at another. Always perpendicular to the lines of flow are the Equipotential Lines or Surfaces, corresponding to lines of equal level or to surfaces of equal pressure in the water. It is evident that no two lines of flow can ever meet, that no two equipotential surfaces can ever meet, and that the lines of flow meet the equipotential surfaces perpendicularly.

Use a shallow sheet of water containing a little salt as the conducting sheet. Let an alternating current supplied by an induction coil enter and leave the water by wires near opposite ends of the sheet. If the ends of two wires connected to a telephone receiver are placed in the liquid at random an alternating current will, in general, pass through the receiver and cause it to buzz. But if the two wires are placed on an equipotential line there will be no current through the receiver and it will remain quiet. In this way the equipotential lines may be traced out and mapped.

Number a page of the report sheet to correspond to the coordinate paper under the glass bottom of the tray. Attach one terminal of the telephone receiver to one edge of

the tray with the end dipping into the liquid near one of the terminals of the main current. Trace out the equipotential line and map it carefully on the report sheet. Move the fixed terminal to another point and map another line and continue until the entire field is mapped. Use special care with the lines close to the current terminals. Draw in the lines of flow, always perpendicular to the equipotential surfaces, with different ink or pencil.

Place a bar of copper (good conductor) along the lines of flow near one terminal and a strip of glass (poor conductor) across the lines of flow near the other terminal. Map carefully the equipotential surfaces and draw in the lines of flow as before. Notice the reciprocal relation between the lines of flow and the equipotential surfaces with respect to the copper and the glass.

N. B. Never leave the induction coil nor allow it to stop working without turning off the current at once.

Discussion:—To insure symmetrical curves the depth of water should be uniform and the salt uniformly distributed. Stir thoroughly. In a large uniform sheet both the lines of flow and the equipotential lines are circles.

Study up and understand thoroughly the action of the induction coil and of the telephone. Why is it necessary to use an alternating current in a liquid conductor?

Notice that with respect to the lines of flow the conducting copper behaves like a deep channel, and the nonconducting glass like an obstruction, in a shallow brook. With respect to the equipotential surfaces the reciprocal is the case.

Experiment 50

Fields of Magnetic Force about a Magnet

A Line of Magnetic Force represents the path which would be traversed by a detached north magnetic pole if free to move, without inertia, in a magnetic field. A de-

tached magnetic pole can never be obtained, but a small magnet in the field will always set itself tangent to the line of force passing through its center and the field may be mapped with the aid of such a magnet.

As an exploring magnet use a very short magnetic needle supported by a fiber so fine that its torsion may be neglected. With this needle, or with a large compass provided for the purpose, determine the magnetic meridian and mark it on the table with a string. All other magnets must be at a distance while this is done.

Fasten a small magnet with wax to a page of the report sheet and turn it into the magnetic meridian. With the exploring needle and a pencil trace the lines of force about the magnet and carry the map over the entire page in order to show how distant lines of the earth's field are affected by the magnet. Pay special attention to critical points where the needle appears to be unstable.

Torsion in the fiber is the most serious source of error. A very fine fiber should be used and if the needle swings round at any point so as to twist the fiber it should be removed to a reference line traced parallel to the meridian and the fiber untwisted until the needle stands parallel to the reference line. Two lines of force can never cross and if they appear to do so the fiber should be examined.

On another page turn the magnet end for end and again map the field. On a third page turn the magnet across the meridian and again map the field.

Discussion:—The lines of flow in the earth's field may be compared to the lines of flow in a broad stream. The magnet would then represent a pipe containing a pump working with the current, against the current, or across the current.

The field of force about the magnet uninfluenced by the earth's field may be mapped by supporting the needle over the table and moving the paper, carrying the magnet, under the needle in such a direction as never

to allow the needle to move out of the meridian. Under these conditions the direction of the force due to the magnet alone, at the point under the needle, is always parallel to the meridian and it may be so traced.

Experiment 51

Magnetic Dip—The Dip Circle

The Dip Circle, used to determine the Magnetic Dip, consists of a long thin magnet with an axle of hard steel supported at the center of a graduated vertical circle. The axle should be cylindrical and should pass through the center of gravity of the needle. It rests upon agate edges or planes and the angle the needle makes with the horizontal is read off on the vertical circle.

Set the plane of the circle parallel to one of the legs and adjust the level and level the instrument as in Experiment 5. Turn to another leg and continue until the bubble stays near the center in all positions of the circle. The axis is then vertical.

Set the plane of the circle in the magnetic meridian either by aid of a compass or by turning the circle until the needle stands exactly vertical and then twisting the plane through 90° measured on the horizontal circle at the base. (Explain fully the last process.) Jar the table gently and read the dip from the graduated circle.

To avoid the error arising from the axle of the needle not being coincident with the center of the vertical circle, read both ends of the needle. To avoid the error due to the magnetic axis not being coincident with the line joining the ends of the needle, turn the axle end for end and read both ends again. To avoid the error due to the zero line not being horizontal, turn the plane of the circle through 180° and repeat the above readings, reversing the

needle as before. To avoid the error due to the axle not being at the center of gravity of the needle, ask an instructor to reverse the magnetism of the neede so that the end which was previously north is now south and repeat all the above readings. The mean of these 16 readings gives the dip.

Discussion:—The above process eliminates the systematic errors which may be expected. Incidentally the errors due to irregularities of the axle and bearing surfaces have been partially eliminated. To further eliminate these it is well to take more than one reading in each position and to read while the needle is in motion instead of letting it come to rest.

One of the sets of readings taken was unnecessary. Determine which set and show why it was unnecessary.

Cut out a paper model of the needle and illustrate for yourself the errors and the methods of avoiding them.

What are the periodic and other variations of the dip?

Experiment 52

Comparison of Magnetic Fields

Let a magnet whose magnetic moment is M, and whose moment of inertia about the point of suspension is A, be suspended free to vibrate torsionally in a magnetic field of strength H. If displaced an angle θ from its position of rest the moment of the force tending to turn the magnet back is $MH \sin\theta$. If the magnet is vibrating freely write down the expression for the angular acceleration at any angle, show that the vibration is simple harmonic motion when the amplitude is small, and that the period is given by $T = 2\pi\sqrt{A/MH}$. Since A and M are constant the period varies inversely as the square root of the strength of the field acting upon the magnet, i. e.

$H_2/H_1 = T^2_1/T^2_2$, or $H_2/H_1 = N_2^2/N_1^2$ where $N =$ the number of vibrations per second.

Take the period of vibration of the magnet on a wooden table near the center of the room. Call the intensity of the field here unity. Find the relative intensity at various other points in the room by taking the period of vibration of the magnet and comparing by the above relation. Test e. g. the regions close to the end and near the middle of a horizontal steam pipe; close to the north and south sides of a brick wall (Is the wall magnetized?); in the bottom of an iron sink and just north or south of the sink; in the horizontal plane through the upper end and again through the lower end of a vertical gas pipe in each case determining whether the pipe is magnetized N or S and testing the region carefully to find the direction and magnitude of the horizontal intensity at several points near the pipe.

Draw an outline map of the room indicating exactly the points tested and the position of any mass of iron which might affect the magnetic intensity. Write in the value and direction of the horizontal intensity found and explain the probable cause of the variations observed in the different parts of the room.

A room intended for magnetic observations is usually built with brass pipes and fittings of all kinds.

Experiment 53

Intensity of the Earth's Magnetic Field—Magnetometer—Telescope and Scale

Experiment 52 gives a method of finding the product MH. This experiment gives a method of finding the ratio M/H whence both the intensity of the magnetic field and the magnetic moment of the magnet may be found.

Place a bar magnet in a stirrup supported by a thread

and find the period of torsional vibration. Compute the moment of inertia:

For a square magnet $A = m\,(L^2/12 + W^2/12)$

For a round magnet $A = m\,(L^2/12 + D^2/16)$

where $m =$ the mass, $L =$ the length, $W =$ the width, and $D =$ the diameter of the magnet. Use the formula given in Experiment 52 to compute MH.

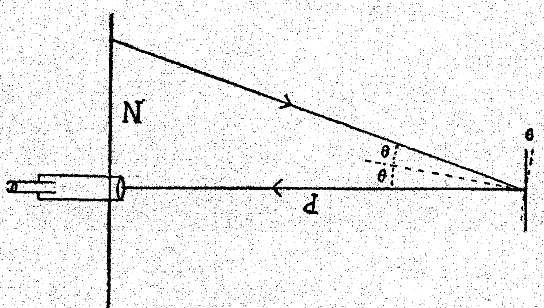
To determine M/H a magnetometer is used with a telescope and scale. The magnetometer consists essentially of a small magnetic needle bearing a mirror and supported by a fine fiber. When the bar magnet is placed exactly east or west of the needle the needle is deflected and comes to rest in a new position such that the moments of the forces exerted upon it by the bar magnet and by the earth's field respectively are equal. Compute these moments, place them equal, and show that

$$M/H = (R^2 - L^2/4)^2 \tan \theta/2R$$

where R is the distance of the center of the bar magnet from the small needle and θ is the angle of deflection.

The magnetometer needle is placed in a box to avoid air currents. The two meter sticks extending east and west are cut off so that their zero ends are at the needle. The distance R of the magnet from the needle may thus be read directly. The magnetometer is so placed that these meter sticks are exactly east and west and it should not be disturbed.

Small angles are frequently read by means of a telescope and scale. The telescope is focussed until the reflection of the scale is seen distinctly upon the cross-hairs.



If now the mirror is turned through an angle θ, since the incident and reflected rays made equal angles with the normal to the mirror, N divisions of the scale will pass across the cross-hairs such that $\tan 2\theta = N/d$ or $\tan \theta = N/2d$ nearly, d being the distance from the mirror to the scale.

Remove the magnet and all magnetic substances (keys, pocket knives, etc.) to a far corner of the room. Adjust the mirror by turning the fiber until the reading is near the center of the scale. Place the magnet, axis east and west, on the meter stick at such a distance as to give a good deflection and take the reading. Interchange the ends of the magnet and read again. Place the magnet at the same distance on the other end of the magnetometer and take two more deflections. Use half the double deflection and compute the angle θ. Compute the value of M/H and hence of M and of H. From M compute the strength of the pole of the bar magnet.

Discussion:—What is the force acting upon each pole of the bar magnet? What is the moment tending to turn the magnet when it is lying in an east-west position? What would be this moment if the horizontal intensity were unity? Note that this is the value of the magnetic moment of the magnet.

Experiment 54

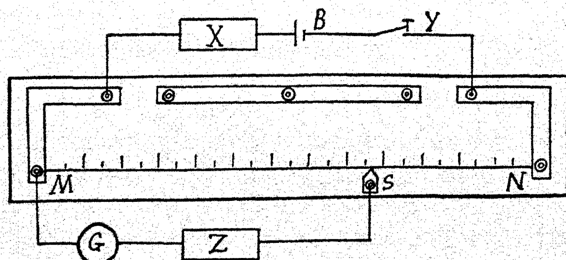
Ohm's Law—Resistance of a Uniform Wire—Shunt—Resistance Box

Ohm's Law:—If a current I flows in a wire between two points whose potential difference is E the ratio E/I remains constant so long as the temperature, etc., of the wire does not change. This constant is called the "Resist-

ance" of the circuit between the two points. If it is represented by R we have

$$E/I = R \qquad \text{or} \qquad E = RI$$

The Resistance of a Uniform Wire is Proportional to the Length.



Connect a battery B, in series with a resistance X and a switch Y, to the ends M and N of a uniform wire. Connect a galvanometer G, in series with a resistance Z, between one end of the wire MN and the movable switch S. Use a telescope and scale (See Exp. 53) to read the galvanometer. Let $E =$ the potential difference (P. D.), $I =$ the current, and $R =$ the resistance between M and N. Let $I' =$ the current and $R' =$ the resistance in the galvanometer circuit between M and S. Let $r =$ the resistance of the uniform wire between M and S, and $e =$ the P. D. between these points. Then by Ohm's law,

$$e = R'I' \qquad \text{and} \qquad I' = e/R'$$

When R' is so large that I' is not an appreciable part of the total current I, we have, with slight error, $e = rI$ and hence

$$I' = \frac{r}{R'} I.$$

The deflection of the galvanometer, if small, is nearly proportional to the current through it and this is proportional to the resistance r between M and S. We are to

show, then, that the deflection, and hence the resistance, is proportional to the length MS.

Begin with the resistances X and Z large and gradually decrease them until the deflection is near the end of the scale when MS includes nearly the whole wire MN. Raise the switch and take the zero reading of the galvanometer. Place the switch 10 cms from M and read again. Slide the switch along and take readings at steps of 10 cms until the whole wire is included and then take similar steps on the return and again note the zero. Show that the deflections are proportional to the lengths of wire between the terminals. Reverse the current and repeat.

Plot a curve using the lengths MS as abscissas and the mean deflections as ordinates. If we assume that the current through the galvanometer is proportional to the length MS this curve shows the relation between the deflections of the galvanometer and the current causing it. Are they proportional?

Discussion:—If too large a current is used in the wire the battery may become polarized and the current I, and so the deflections, decrease. If the wire becomes heated the resistance increases.

The Shunt.

The potential drop between M and S is the same along both branches of the divided circuit, i. e.

$$I' R' = Ir \qquad \text{or} \qquad I'/I = r/R'$$

If I represents the current on the straight wire between M and S the above relation holds rigidly whatever be the relation between the resistances. Thus the current in either branch may be controlled at will by adjusting the resistance of either. This arrangement is called a "Shunt" and it is very commonly used to obtain small currents.

If the current in the galvanometer branch above is

small, i. e. if the resistance is large, compared with that of the other branch, we have, with slight error,

$$e/E = Ir/IR = r/R.$$

This is a method of using the shunt to obtain for use a small fraction of a known potential difference. The wire MN may be very long and may be wound on the spools in a "resistance box." In this case the terminals of the shunt circuit may be placed across any desired portion of the total resistance.

The resistance of a galvanometer is 1000 ohms. What resistance should be used as a shunt that 1/10 of the cur rent may pass through the galvanometer?

A battery of 50 volts E. M. F. is connected to a resistance box containing 10000 ohms. What is the P. D. at the terminals of 1 ohm? Where should the terminals of a shunt be placed to obtain 1/10 volt for use?

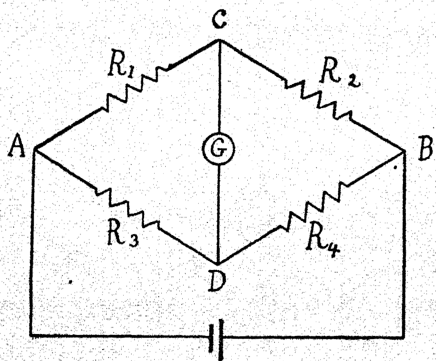
Resistance Box.

A resistance box is a box containing a series of spools of wire of different resistances. The terminals of each spool are connected to heavy copper blocks upon the top of the box. These blocks may be connected by means of a conical plug. When the plug is in the socket (it should be put in with a slight twist to insure good contact) the coil below that plug is "short-circuited," the current passes from block to block through the plug, and the resistance is practically zero. When the plug is removed the current must pass through the coil below and the resistance is that marked on the box opposite the socket. The resistances of the coils are so graduated that any resistance from that of the smallest coil to the full capacity of the box may be obtained in steps equal to the resistance of the smallest coil.

Experiment 55

Measurement of Resistance—Wheatstone's Bridge

Wheatstone's Bridge is a device for comparing resistances.



Let R_1, R_2, R_3, and R_4, represent the resistances of the four arms of the rectangle represented in the figure. If a battery is connected to the points A and B the fall of potential in the two branches of the circuit is the same. If the terminals of a galvanometer are connected at random to the two branches there will be a deflection of the needle, but one terminal may be moved (as in Experiment 49) until there is no deflection. Then the two terminals C and D are at the same potential and

$$R_1/R_2 = R_3/R_4.$$

If the ratio R_3/R_4 and the resistance R_2 are known, the unknown resistance R_1 may be found.

The Wire Bridge.

Connect the battery, through a reversing switch, to the ends of the wire used in Experiment 54. In one of the gaps of the bridge connect a resistance box and in the other an unknown coil of wire. Connect one terminal of the galvanometer between these and connect the other to the movable switch. The two parts of the meter wire form the arms AD and DB of the bridge. Use a large resistance in the galvanometer circuit and a few ohms in the battery circuit until a preliminary adjustment is made.

Remove the ten ohm plug from the box in the bridge, place the switch near the middle of the wire, and adjust the resistance in the box until the bridge is approximately balanced. Increase the sensitiveness by removing resistance from the battery and galvanometer circuits and finish the balancing by moving the switch until there is no deflection. Read the position of the switch, find the lengths of the two parts of the wire, and compute the unknown resistance, remembering that the resistances of the two parts of the wire are proportional to the lengths.

To eliminate the errors due to thermal E. M. Fs. at the junctions of the metals reverse the current by means of the reversing switch and balance the bridge again. (Make a drawing of the reversing switch, with its connections, upon the report sheet.) To eliminate errors due to irregularities in the meter wire interchange the coil and box and balance again. Reverse the current again also.

Measure the resistance of another coil. Measure the resistance of the two when connected in series and when connected in parallel. Verify the laws:

$$R = R_1 + R_2 \qquad \text{(Series)}$$
$$1/R = 1/R_1 + 1/R_2 \qquad \text{(Parallel)}$$

Discussion:—Note that the battery and galvanometer may be interchanged.

An error in setting the switch causes the least error in the result when the switch is near the middle of the wire.

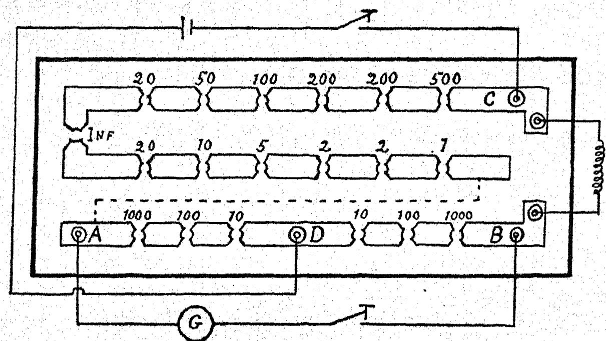
The form of bridge used almost universally is the "postoffice box" described under Experiment 56.

Experiment 56

Postoffice Box—Galvanometer and Battery Resistance

The Postoffice Box, first used in the British postoffice telegraph service, is a compact form of Wheatstone's

bridge. (See diagram.) The bridge wire is wound on two corresponding sets of spools in the arms DA and DB.



The adjustable arm AC is on the same box. The unknown coil is connected between BC. The lettering is the same as on the diagram of Experiment 55 except that the battery and galvanometer are interchanged.

In using this form of bridge one plug is taken from each of the "ratio" arms. Instead of moving the switch the resistance of the third arm is adjusted until the bridge is balanced. If no balance can be obtained with the resistances in the box find the two resistances which most nearly give a balance, take the galvanometer deflections, and compute the resistance which would give an exact balance.

(1) Resistance of a Coil of Wire.

Using the method just described measure the resistance of one of the coils used in Experiment 55.

(2) Resistance of a Galvanometer by Thomson's Method.

Connect the galvanometer whose resistance is required in the arm BC in place of the unknown resistance. There is always a current through the arm BC which will cause a steady deflection of the galvanometer. Omit the galvanometer in the circuit AB, leaving only the switch. When

this switch is closed there will be a current through this circuit unless the bridge is balanced. This current will change the P. D. between A and B, and thus the currents in all the other arms, including BC, will be changed. This will change the galvanometer deflection which will thus indicate a current in AB. When the bridge is balanced there will be no current in AB and hence no change in the deflection of the galvanometer. If there is some range of adjustment through which the bridge appears to be balanced find the adjustments which just show deflections in opposite directions and take the mean.

To obtain a current through BC small enough to avoid throwing the galvanometer deflection off the scale connect the battery to the terminals of a resistance box and lead a small shunt to the battery terminals of the postoffice box. Use a deflection as large as convenient.

(3) **Resistance of Battery by Mance's Method.**

Replace the galvanometer between A and B and place the battery in the arm BC, leaving only a key in the direct circuit between D and C. The battery in BC will maintain a steady system of currents in the arms of the bridge and in the galvanometer. If a new E. M. F. is now impressed upon the circuit DC in either direction the currents resulting will be superimposed upon those already in the bridge and will not affect their distribution, hence they may be ignored and the resistance of the arm BC may be measured in the usual way. Closing the switch in DC reduces the P. D. between D and C almost to zero, which is equivalent to introducing a new E. M. F. in the arm. When the bridge is balanced the superimposed currents caused by closing the switch will cause no change in the deflection of the galvanometer.

To avoid throwing the galvanometer deflection off the scale connect the wires from A and B to the terminals of a resistance box and lead a small shunt to the galvanometer terminals. Use a deflection as large as convenient.

Discussion:—The above method may be made much more sensitive by using larger currents in the galvanometer. This necessitates bringing the deflection back onto the scale by twisting the suspension fiber in a d'Arsonval or by adjusting the control magnet in a Thompson galvanometer. This is a troublesome process for one unfamiliar with the instrument and the student is not asked to attempt it.

Polarization of the cell may cause changes in the resistance of the cell and so make it difficult to obtain consistent values for this resistance.

Experiment 57

Sensitiveness and Resistance of a Galvanometer

The "Sensitiveness" of a Galvanometer is the current, in amperes, required to give a deflection of one scale division when the scale is one meter distant from the mirror.

Use the galvanometer whose resistance was measured in Experiment 56 but assume the resistance unknown. Connect a battery cell whose E. M. F. is known (the E. M. F. of a gravity cell is about 1 volt) to a resistance box and lead a small shunt to the terminals of the galvanometer. Let $E =$ the potential difference applied to the galvanometer, $R =$ the galvanometer resistance, $D =$ the deflection and $d =$ the distance of the scale from the mirror expressed in meters. Then the current through the galvanometer is $I = E/R$, that required for one scale division is E/RD and the sensitiveness is $S = Ed/RD$.

Obtain a second equation containing S and R by placing a resistance box in series with the galvanometer and put in enough resistance to reduce the deflection to approximately one-half its former value. Let $r =$ the resistance added. Then $S = Ed/\,(R+r)\,D'$. From these two equations both R and S may be computed.

Vary the experiment by using a different resistance and by varying the potential difference used.

The sensitiveness of a galvanometer is sometimes expressed in "megohms." (1 megohm = 1000000 ohms). A galvanometer whose sensitiveness is 1 megohm gives a deflection of 1 scale division upon a scale 1 meter distant when an E. M. F. of 1 volt is applied to the terminals through a resistance of 1 megohm placed in series with the galvanometer. What is the sensitiveness in megohms of the galvanometer you have measured?

Experiment 58

Resistance and Electromotive Force of a Battery—Ammeter and Voltmeter—Divided Circuits

Suppose a gravity cell is used. When no current flows through the cell the potentials of copper, zinc, and liquid may be represented as in Figure 1, where AB represents the E. M. F. of the cell. An electrometer connected to the terminals of the cell would measure accurately this potential difference between the copper and zinc which is the E. M. F. of the cell. A voltmeter allows a small current to flow and thus does not measure accurately the E. M. F. of the cell.

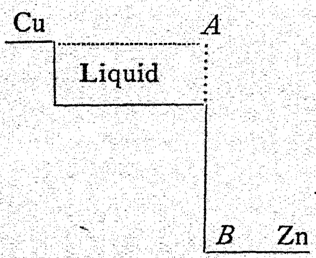


Fig. 1

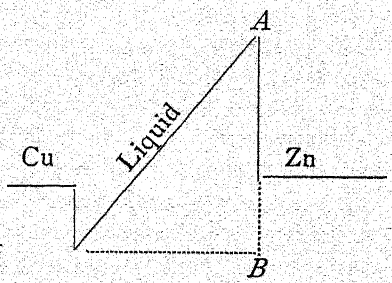


Fig. 2

When a current flows the potential of the copper

drops. If we connect the copper and zinc by a short wire they are at practically the same potential, but the two extremities of the liquid are at different potentials, as represented in Figure 2, the difference, AB, representing again the E. M. F. of the cell. A voltmeter connected to a cell thus short-circuited would read zero.

In general the total potential drop in all parts of the circuit is equal to the E. M. F. of the cell and the drop in any portion of the circuit is proportional to the resistance of that portion (P. D. $= RI$). The voltmeter, when connected to the zinc and copper, measures the drop outside only. Hence, if $e =$ the potential drop inside the cell, $V =$ the potential drop in the external circuit, $r =$ the internal resistance of the cell, and $R =$ the resistance of the external circuit,

then $E = e + V$, and $e/V = r/R$

whence $E/V = (R+r)/R$ or $E = V(R+r)/R$

(1) Find the E. M. F. and the Internal Resistance of a Cell.

Connect the voltmeter, whose resistance R_v is known, directly to a gravity cell. If V is the reading of the voltmeter, the E. M. F. of the cell is

$$E = V(R_v + r) / R_v$$

Next connect the ammeter, whose resistance R_a is known, to the cell, take the reading, and disconnect immediately to avoid polarizing the cell. If C is the reading

$$C = E/(R_a + r).$$

From these two equations E and r may be found.

Both E and r are subject to change due to polarization. The current should never be left flowing longer than is necessary to take a reading. Change conditions if possible and take the readings two or three times.

(2) Divided Circuits.

Connect an ammeter, a voltmeter, and a resistance box to a cell as in Figure 3, making R_e equal 10 ohms or more. Take the voltmeter reading V and the ammeter reading C_a simultaneously.

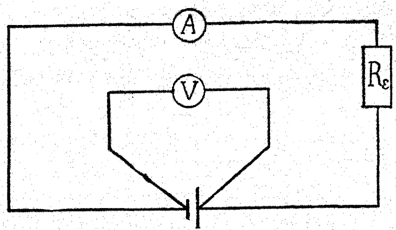


Fig. 3.

(A) **Show that the potential drop within the cell is proportional to the resistance of the cell.**

In the external circuit the current has two paths, one through resistance R_v and one through resistance R_a+R_e. The effective external resistance R is given by $1/R = 1/R_v + 1/(R_a+R_e)$. Solve for R and show that

$$r/R = (E-V)/V.$$

Usually R_v is large and R_a small. Then $R = R_e$ nearly, but this cannot be assumed when accuracy is needed.

(B) **Show that the current flowing in each branch of the circuit is inversely proportional to the resistance of that branch, i. e.**

$$C_a/C_v = \mathrm{R}_v/(\mathrm{R}_a+\mathrm{R}_e)$$

The current C_v cannot be measured directly but

$C_a/(C_v+C_a) = R_v/(R_v+R_a+R_e)$ whence, since

$$C_v'+C_a = \frac{E}{R+r}, \qquad C_a = \frac{R_v}{R_v+R_a+R_e} \times \frac{E}{R\times r}$$ Corret th

Compute C_a from the above and compare with the measured value. Does the law hold?

Discussion:—The student should make himself acquainted with the construction of an ammeter and of a voltmeter and with the composition and advantages of a gravity cell and of other forms in common use. He should

also learn what determine the resistance and the E. M. F. of the cell.

How may a voltmeter be used to measure an E. M. F. greater than that for which the instrument was intended?

How may an ammeter be used to measure a current greater than that for which the instrument was intended?

Experiment 59

Tangent Galvanometer — Electrolysis—Electro-chemical Equivalent

A Tangent Galvanometer consists of a large circle of wire with a small magnetic needle at the center. If a current i passes through the coil when its plane is in the magnetic meridian the needle will be deflected through an angle θ such that $i = H \tan \theta / G$ where $H =$ the horizontal component of the earth's magnetic force and $G =$ the "galvanometer constant." G may be computed from the dimensions of the coil. If $n =$ the number of turns of wire and $r =$ the radius of the circle (measured to the center of the wire) $G = 2\pi n / r$. H may be determined, for the position of the galvanometer, by the method of Experiment 52, using for the value at the magnetometer that found in Experiment 53. In this way the magnitude of a current may be measured in absolute units.

The Gas Voltameter consists of two graduated glass tubes with stop-cocks at the top and platinum electrodes near the bottom. These tubes are connected at the bottom with each other and with a third tube carrying a reservoir at the top. The tubes are filled with dilute sulphuric acid (10% by weight). When a current of electricity passes between the electrodes, electrolysis takes place and hydrogen is given off at one electrode and oxygen at the other. The gases collect in the tubes above the electrodes where the volumes may be measured. Note that the volume of the hydrogen is about twice that of the oxygen.

The Electro-chemical Equivalent of a substance is the mass of that substance liberated by one C. G. S. electro-magnetic unit of electricity.

Determine the Electro-chemical Equivalent of Hydrogen.

The mass of each gas liberated in the voltameter is proportional to the quantity of electricity which passes. We need to know this quantity and the mass of each gas which it liberates. Connect in series a battery, a resistance box, a voltameter, and a tangent galvanometer the last through a reversing switch. The current should be sufficient to give a deflection of about 25° with a resistance of a few ohms in the circuit. See that the needle swings freely in both directions. Start the current and note the time. Occasionally reverse the current through the galvanometer and take the mean of the readings. If the current tends to fall off decrease the resistance in the resistance box enough to keep the deflection up to the original value (the average value of a varying angle must not be used since the tangent is not proportional to the angle). Let the current flow until the hydrogen tube is more than half filled with gas. The quantity of electricity which has passed equals iT where T is measured in seconds.

To find the mass of gas liberated find the pressure on the gas and the temperature and compute the volume under standard conditions. The pressure inside the tube is due partly to the hydrogen gas and partly to the water vapor. The two together equal the atmospheric pressure plus the pressure exerted by the excess column of liquid in the central tube. The density of this liquid (composition given above) is about 1.05. Compute the pressure on the hydrogen gas and call this H'. If P' is the pressure of the water vapor (See Appendix) the pressure exerted by the gas alone is $P = H' - P'$. Read the volume of the gas in the tube, compute the volume under standard conditions

(Exp. 36), find the mass (density of hydrogen under standard conditions = .000090) and compute the electro-chemical equivalent.

The density of oxygen under standard conditions = .00143. Assume the volume of the oxygen to be one-half that of the hydrogen and compute the electro-chemical equivalent of oxygen.

Discussion:—If the electro-chemical equivalent of hydrogen is taken as known this method may be used to measure a steady current in absolute units. In this way the galvanometer constant may be determined experimentally or an ammeter may be calibrated. The method may also be used to determine the horizontal component of the earth's magnetic force.

The silver voltameter deposits silver from a solution of silver nitrate upon a silver electrode. Results obtained are more accurate than those obtained with the gas voltameter. For large currents the copper voltameter, which deposits copper from a solution of copper sulphate, is used.

Electrolysis is extensively used to extract metals from their ores, for electro-plating, etc.

Experiment 60

Polarization of a Cell

When a voltaic cell is in use electrolysis takes place and hydrogen usually appears at the positive pole (carbon, copper, etc.). This hydrogen is troublesome for two reasons: first, it clings in bubbles to the surface of the plate, increasing the internal resistance and so decreasing the current; second, it sets up a separate E. M. F. in the opposite direction, thus decreasing the current by decreasing the E. M. F. of the cell.

To prevent this deposit of hydrogen the positive plate is immersed in some strong oxydizing agent which combines with the nascent hydrogen to form water and some

other unobjectionable material. If a large or long-continued current is taken off, however, the hydrogen may be liberated faster than it can be disposed of, in which case the current falls off, and the cell becomes polarized. If now the circuit is opened the hydrogen gradually disappears and the E. M. F. and the resistance of the cell return to their normal values.

Plot the Polarization and Restitution Curves of a Leclanche Cell.

Connect in series a cell, a resistance coil of about one ohm, and a key. In parallel with the last two connect a voltmeter to the terminals of the cell. (See Fig. 3, Exp. 58. The key replaces the ammeter.) When the key is open the reading of the voltmeter is directly the E. M. F. of the cell. (The resistance of the voltmeter is so great that the small current which flows may be neglected.) When the key is closed a current flows through the resistance R. The voltmeter then indicates the difference of potential between the terminals of this small resistance. It will be noticed that if the key be held down the pointer of the voltmeter moves slowly over the scale indicating a steady decrease of the potential difference. Make preliminary trials with one cell and then use a fresh cell for the final readings.

Polarization.

Read the voltmeter and record the reading as the initial E. M. F., then close the key and read the voltmeter again for the P. D. Take readings of the P. D. every few seconds at first, then at longer intervals. Immediately after each reading open the key for an instant, long enough to get a reading of the E. M. F., but take the reading without waiting for the needle to come to rest as the cell is depolarizing. Continue until further polarization of the cell becomes very slow. Record the time at which each reading was taken.

The current flowing through the circuit may be found since $I = \text{P. D.}/\text{R}$, also the internal resistance of the cell since $I = \text{E. M. F.}/(R+r)$. Compute each of these for each reading.

Restitution.

When the cell is polarized begin another set of readings similar to those above. This time the key is to be left open except for an instant at short intervals when P. D. readings are to be taken. Continue until the recovery of the cell becomes very slow.

Plot on the report sheet three curves for each part, using time as abscissas in each case, and the electro-motive force, current, and resistance of the cell, respectively, as ordinates. The three curves may be placed on a single plot.

Experiment 61

Mechanical Equivalent of Heat—Electrical Method

The Mechanical Equivalent of Heat is the number of ergs of mechanical energy which are equivalent to one calorie.

When a current flows in a wire the energy expended per second in heating the wire is EI or RI^2 and this is expressed in ergs if R and I are expressed in C. G. S. electromagnetic units. If the wire is placed in water contained in a calorimeter the heat generated in time T may be measured. $H = (m+w)\,(t-t_0)$, allowance being made for radiation. Then the mechanical equivalent is

$$J = RI^2\,T/H.$$

Compute the water equivalent of the calorimeter and stirrer. Weigh the water to be used and put in the wire ready for use. Be sure the coils of the wire do not touch each other or the sides of the calorimeter and that the coi is completely covered by the water. Measure the resist-

ance of the coil when in position in the water. Connect the coil, an ammeter, and a variable resistance in series to the switch. Do not close the switch until an instructor has seen your connections.

Allow the current to flow until a suitable rise in temperature, 15 or 20 degrees, has been obtained, noting the time carefully. Keep the current constant by means of the variable resistance. It is not safe in this experiment to use the average of a varying current. Why? Keep the water gently stirred throughout the run. When the current is stopped note the rate of cooling for the radiation correction. Measure the resistance of the coil again at the higher temperature and take the mean for R.

Compute the value of the mechanical equivalent remembering that one ampere $= 1/10$ C. G. S. unit and one ohm $= 10^9$ C. G. S. units.

Experiment 62

The Ballistic Galvanometer—Comparison of Capacities—Comparison of Electromotive Forces

The ballistic galvanometer measures a quantity of electricity rather than a current. When a condenser is discharged through the galvanometer the charge passes in a small fraction of a second and the first throw is nearly proportional to the quantity of electricity which has passed through the instrument, i. e. $Q = KD$ nearly.

Since the moving system is always a little "damped" the first throw, D_1, falls somewhat short of the value it should have. To find the correction note also the second throw, D_2, in the same direction as the first. The difference is the amount lost in four quarter swings. Hence the amount lost in the first quarter swing is approximately

one-fourth this difference and this should always be added to the first swing, i. e.

$$D = D_1 + (D_1 - D_2) / 4$$

To Stop the Vibration.

For a Thomson galvanometer pass a current at proper intervals through an auxiliary coil placed outside the case.

For a d'Arsonval galvanometer short-circuit the moving coil and the current induced by the rotation of the coil in the magnetic field will stop the motion. (Lenz' law.)

(1) Compare the Capacities of a Set of Condensers.

If two condensers are charged to the same potential difference the quantities of electricity are proportional to the capacities ($C = Q/E$) and if discharged through a ballistic galvanometer the deflections are proportional to the capacities.

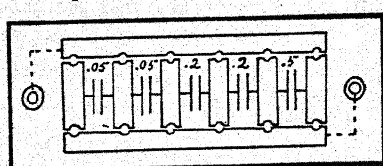


Fig. 1.

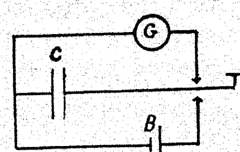


Fig. 2.

The capacities in a box may be arranged as in Figure 1. Never place plugs in the holes at both ends of the same block. Why? Connect the apparatus as in Figure 2. Obtain throws with about five different capacities and show that the throws are proportional to the capacities.

(2) Compare the Electromotive Forces of a Number of Cells.

If the same capacity is used the quantities, and so the deflections, are proportional to the E. M. Fs. ($E = Q/C$). Use a Carhart-Clark cell as standard. The E. M. F. of this cell is about $E_t = 1.440\,(1 - 0.0004\,(t - 15))$, where t is the temperature inside the cell. Find the E. M. Fs. of

the following cells and look up the composition of each and the chemical action within each:—Gravity, Bichromate (Remove the zinc from the liquid after using), Leclanche or Samson, Dry, Lalande, Storage, etc.

Discussion:—Note that no current flows through the cell, hence this method gives the E. M. F. directly without polarization.

Note that the E. M. F. is independent of the size of the cell.

Experiment 63

Earth Inductor—Magnetic Dip

When a coil of wire is moved in a magnetic field an E. M. F. is induced in the coil equal to the rate at which lines of magnetic force are cut by the wires. If the coils form a closed circuit a quantity of electricity passes round the circuit equal to the number of lines of force cut divided by the resistance of the circuit. If a ballistic galvanometer (See Exp. 62) is included in the circuit the throw of the galvanometer, when the coil is moved, is proportional to the number of lines of force cut.

The earth inductor consists of a coil of wire so mounted in a frame that the plane of the coil may be rotated through 180°. The frame is so mounted that the axis about which the coil rotates may be inclined at any angle to the horizontal. Let $F =$ the number of lines of magnetic force passing through each square centimeter of a plane perpendicular to the direction of the force, $A =$ the area of the coil, $n =$ the number of turns of wire in the coil, $R =$ the resistance of the entire circuit, and $\theta =$ the magnetic dip. If the plane of the coil is perpendicular to the direction of the magnetic force the total number of lines through each turn of the coil is FA, and the quantity of electricity which passes through the galvanometer when

the coil is turned through 180° is given by $Q = 2nFA/R$. If the plane of the coil is horizontal the quantity of electricity which passes when the coil is turned through 180° is $Q_1 = 2nFA \sin \theta/R$. If the plane of the coil is vertical and perpendicular to the magnetic meridian the quantity of electricity which passes when the coil is turned through 180° is $Q_2 = 2nFA \cos \theta/R$. Thus we have $\tan \theta = Q_1/Q_2 = D_1/D_2$ since the deflections are proportional to the quantities of electricity which pass through the galvanometer.

Place the instrument so that the axle of the square frame is perpendicular to the magnetic meridian. Bring the needle of the ballistic galvanometer to rest by the device provided (See Exp. 62). With the plane of the coil horizontal take several throws in each direction, bringing the needle to rest and reading the zero before each throw. If the damping is large correct as in Experiment 62. The coil should be turned quickly but without jarring the coil or the table.

Turn the frame vertical and repeat. Compute the magnetic dip.

The horizontal component of the earth's field was found in Experiment 53. Compute the total intensity and the vertical component.

If the needle cannot be brought quite to rest turn the coil at the instant the needle is at its maximum swing in the direction in which the deflection is to occur and determine the *additional* deflection due to turning the coil.

Experiment 64

Distribution of Magnetic Intensity Along a Bar Magnet

The throw of a ballistic galvanometer is proportional to the quantity of electricity which passes through the

instrument (Experiment 62). If the electricity is induced in a coil of wire connected to the galvanometer the quantity is proportional to the number of lines of magnetic force cut by the coil (Experiment 63). Thus the number of lines of force in different parts of a magnetic field may be compared by comparing the throws of a galvanometer when a coil of wire is suddenly withdrawn from the regions to be compared. If the coil is moved from one point in the field to another the throw is proportional to the *change* in the number of lines through the coil, and, if it is always held perpendicular to the direction of the intensity, this change represents the change in the intensity of the field.

Explore the Field Along a Bar Magnet.

With a battery and shunt pass a small current through the galvanometer. Note the terminal at which the current enters and the direction of the throw.

Attach a coil of wire to a meter stick in such a way that a magnet may be slid by steps along the meter stick, through the coil, and its position be noted at each step. Place the magnet upon the meter stick so far from the coil that its motion does not perceptibly affect the galvanometer. Slide the magnet along the bar, step by step, noting at each step the position of the magnet, and the magnitude and direction of the throw. Move the magnet through the coil two or three times in each direction.

Remember that the magnitude of the throw is proportional to the *change* in the number of lines through the coil. By Lenz' law the direction of the induced current is always such as to set up a magnetic field which will oppose the motion which induces the current. By this law determine which pole of the magnet first approaches the coil. Plot a curve representing the magnet and the intensity of the field along the magnet and beyond the ends, in both directions, to the points where the field is practically zero.

Experiments in Light

Experiment 65

Comparison of Intensity of Light Sources—Photometer

If a conical bundle of rays emitted by a light source fall upon a screen placed at a distance from the source, the area of the screen illuminated by these rays is proportional to the square of the distance of the screen from the source and the intensity of illumination of one square centimeter of the screen is inversely proportional to the square of this distance. Thus if two portions of a screen, independently illuminated by two light sources, have equal illumination, the relative intensity of the sources is proportional to the squares of their distances from the screen.

A photometer is a device for illuminating adjacent portions of a movable screen by the two light sources whose intensities are to be compared. When the two portions are equally illuminated

$$I_1/I_2 = D_1^2/D_2^2.$$

Use Foucault's form of photometer. Examine the photometer carefully and draw diagram. For light sources use two forms of gas or oil lamps. Do not use intensities differing too widely.

The difference in color of two lights of different kind is usually a serious difficulty. Compare the component colors of the lights separately by using in turn several pieces of celluloid or glass of different colors held either before the photometer or before the eyes. With each color make several settings and then turn the photometer over

and repeat in order to eliminate any error resulting from difference in the two sides of the photometer. Record readings systematically and compute the relative intensity for each color separately.

To correct for any change in the intensities of the sources during the experiment take the final readings with the same color of celluloid with which the first were taken.

Care must be taken to have both lamps so shaded that they are not directly visible from the position of the observer.

Make one set of measurements with the gas turned high and another with the gas turned low. For each set of measurements plot a curve of which the ordinates represent the relative intensities of the colors red, yellow, green, blue, etc. Plot both curves on one diagram. What change has taken place in the composition of the light?

Experiment 66

Spherical Mirrors

Let u = the distance of an object from a mirror, v = the distance of its image from the mirror, F = the distance of the principal focus from the mirror, and R = the radius of the mirror. Then, if distances measured in front of the mirror are considered positive and those measured behind the mirror negative, the relation

$$1/u + 1/v = 2/R$$

holds approximately for all spherical mirrors if only a small portion of the surface is used.

The principal focus of the mirror is the position of the image when the object is at an infinite distance, i. e. when the rays falling upon the mirror from any one point of the

object are sensibly parallel. If $u =$ infinity, $v = R/2 = F$ by definition.

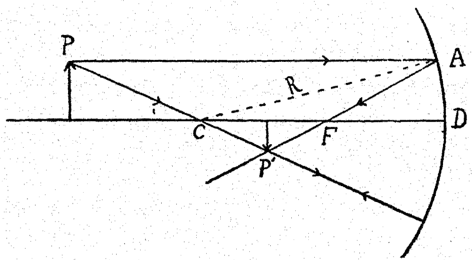


Fig. 1.

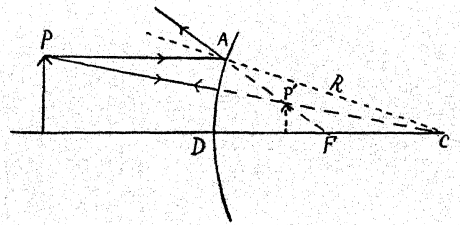


Fig. 2.

An axis of the mirror is a line drawn through the center of curvature (C) of the mirror to a point on the mirror. The principal focus (F) is the point on this axis midway between the center and the mirror. A ray of light from a point P, passing to the mirror along the line PA parallel to the axis CD, will be reflected along a line which passes through the principal focus, the incident and reflected rays making equal angles with the radius CA. A ray from P, passing to the mirror along a line through the center of curvature, will meet the mirror normally and be reflected back upon itself. These two rays, and all other rays from P which fall upon the mirror (produced backward if necessary, Fig. 2) will meet a point P′ which is the focus of P. P and P′ are "conjugate" foci. If the rays actually meet at P′ (Fig. 1) the image is "real" If the rays meet at P′ only when produced backward (Fig. 2) the image is "virtual."

There is a third ray from P whose path to P′ may be traced independently. Locate the image by means of this ray and one of those already used. Construct diagrams illustrating the formation of the image in each of the cases used below.

(1) Concave Mirror (Fig. 1)—Radius of Curvature.

R is positive in the above formula. At what point are the object and image equidistant from the mirror? Under what conditions is v negative (image virtual)?

Allow light from the sun or from a distant landscape ($u =$ infinity) to fall normally upon the mirror and throw the reflected light upon a screen, shaded if necessary. When the image is most distinct the screen is in the principal focus. Measure its distance from the mirror and compute the radius of curvature.

Place a pin in a support in front of the mirror and close to it. Slowly draw away the pin and watch the image carefully. When the image becomes very indistinct (this setting cannot be made accurately on account of the unconscious adjustment of the lens in the eye) measure the distance of the pin from the mirror. This is roughly the distance of the principal focus. By standing far back a large, inverted, real image of the pin can usually be seen. Draw the pin further from the mirror whereupon this real image moves toward the mirror until the pin and image meet. Where?

Place the pin and its inverted image accurately together, point to point, by the parallax method. If the two points are together they will appear together wherever the eye is moved. If they are not together that further from the eye will appear to move in the direction the eye is moved. When accurately together they are at the center of the mirror. Measure R.

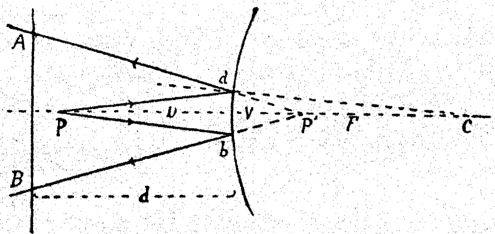
Draw the pin still further away. The image continues to approach the mirror. In some convenient position

locate the image by placing another pin below it, point to point. Notice that the image of each pin stands exactly over the other pin. A pair of conjugate foci are thus located. Compute R.

How near the mirror may the real image approach?

(2) Convex Mirror (Fig. 2)—Radius of Curvature.

R is negative in the above formula. Can a real image ever be formed? Try to form a real image of the sun as you did with the concave mirror. Can the parallax method be used for locating a virtual image?



With a bit of wax fasten vertically upon the face of the mirror a strip of paper ab about one centimeter wide. Support a pin at a distance u in front of the mirror. Beyond the pin, at a distance d from the mirror support horizontally a meter stick. View the image of the pin over the meter stick and take the readings on the meter stick immediately under the line of sight when the image of the pin point is just visible at one edge of the paper strip. Take a similar reading at the other edge. The difference in these readings is AB. From the similar triangles whose vertices are at P′, the position of the image, we have $v/(v+d) = ab/AB$. Compute v and then R from the original formula, remembering that v and R are measured behind the mirror and so should be given negative signs in the formula. Repeat with different values of u and d.

Remove the pin, throw sunlight upon the mirror, and

catch the shadow of the strip of paper upon the meter stick. The width of the shadow $= AB$, $u =$ infinity, and $v = F = R/2$. Determine R.

Experiment 67

Focal Length of a Lens

Let $u =$ the distance of an object from a lens (considered positive when measured in front of the lens), $v =$ the distance of the image and $F =$ the distance of the principal focus from the lens (both considered positive when measured behind the lens). Then the relation

$$1/u + 1/v = 1/F$$

holds approximately for the central portion of a spherical lens.

The principal focus of the lens is the position of the image when the object is at an infinite distance, i. e. when the rays falling upon the lens from any one point of the object are sensibly parallel. If $u =$ infinity, $v = F$ by definition.

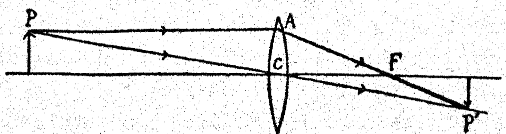


Fig. 1.

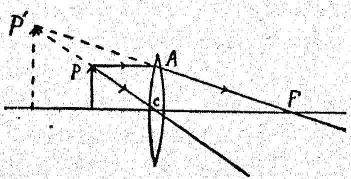


Fig. 2.

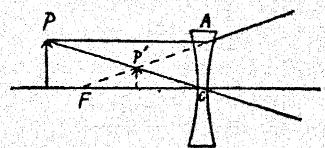


Fig 3.

The axis of the lens is the line drawn through

the centers of curvature of the two surfaces of the lens. A ray of light from a point P, passing to the lens along the line PA, parallel to the axis CF, will be refracted along a line which passes through the principal focus. A ray from P, passing to the lens along a line through the optical center of the lens, will pass through without deviation. These two rays, and all other rays from P which fall upon the lens (produced backward if necessary, Figs. 2 and 3), will meet in a point P′ which is the focus of P. P and P′ are "conjugate foci." If the rays actually meet at P′ (Fig. 1) the image is "real." If the rays meet at P′ only when produced backward (Figs. 2 and 3) the image is "virtual."

There is a third ray from P whose path to P′ may be traced independently. Locate the image by means of this ray and one of those already used. Construct diagrams illustrating the formation of the image in each of the cases used below.

(1) Converging Lens (Figs. 1 and 2)—Focal Length.

F is positive in the above formula. Under what conditions are the object and image equidistant from the lens? Under what conditions is v negative (image virtual)?

Allow light from the sun or from a distant landscape ($u =$ infinity) to fall upon the lens and throw the image upon a screen, shaded if necessary. When the image is most distinct the screen is in the principal focus. Measure its distance from the lens, i. e. the "focal length" of the lens.

Support a pin in place of the screen used above and locate the position of a point in the image of the distant landscape by the parallax method. If the pin point coincides with the point of the landscape selected they will appear together wherever the eye is moved. If they are not together that further from the eye will appear to move in the direction the eye is moved. When they are

accurately together the pin is in the principal focus. Measure the focal length.

Use a nearer object, such as another pin in front of the lens but at a distance from it equal to three or four times the focal length, and locate its image by the parallax method, bringing the first pin and the image of the second pin together point to point. Notice that the image of each pin stands exactly over the other pin. A pair of conjugate foci are thus located. Compute *F*.

Draw the more distant pin nearer to the lens and note that the image recedes from the lens and finally goes to infinity. At this point the pin is roughly in the principal focus of the lens. The setting cannot be made accurately on account of the unconscious adjustment of the lens in the eye. A large, erect, virtual image of the pin can now usually be seen through the lens (Fig. 2). As the pin is drawn nearer the lens this virtual image approaches the lens and the pin and image finally coincide at the lens.

(2) **Diverging Lens (Fig. 3)—Focal Length.**

F is negative in the above formula. Can a real image ever be formed? Try to form a real image of the sun as you did with the converging lens. Can the parallax method be used for locating a virtual image?

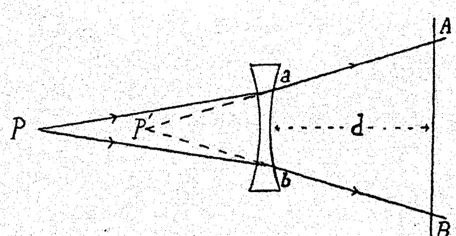


Fig. 4.

With a bit of wax fasten vertically upon the face of the lens a strip of paper *ab* about 1 cm wide. Support a pin at a distance *u* in front of the lens. Behind the lens,

at a distance d support horizontally a meter stick. View the image of the pin over the meter stick and take the reading on the meter stick immediately under the line of sight when the image of the pin point is just visible at one edge of the paper strip. Take a similar reading at the other edge. The difference in these readings is AB. From the similar triangles whose vertices are at P′, the position of the image, we have $v/(v+d) = ab/AB$. Compute v and then F from the original formula, remembering that v and F are measured in front of the lens and so should be given negative signs in the formula. Repeat with different values of u and of d.

Remove the pin, throw sunlight upon the lens, and catch the shadow of the strip of paper upon the meter stick.

The width of the shadow $= AB$, $u =$ infinity, and $v = F$. Determine F.

A real image cannot be formed by a diverging lens alone but if the incident rays are converging toward a point, instead of diverging from a source, the rays may still be converging after passing through the lens and a real image may be formed.

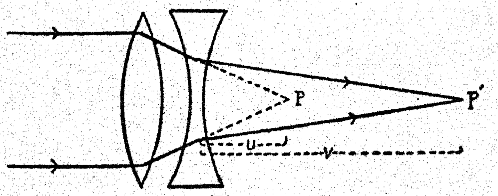


Fig. 5.

Place a pin in coincidence with the image of a distant object formed by a short-focus converging lens. Now place the diverging lens close to the converging lens, between it and the pin. The distance from the diverging lens to the pin is u and it is negative. Move the pin to the new image. The distance is now v. Substitute in the original formula and compute F.

Discussion:—A diverging lens whose focal length is 150 cms is placed immediately behind a converging lens whose focal length is 100 cms. What is the focal length of the combination? If the diverging lens is placed 20 cms behind the converging lens where is the principal focus of the combination?

The above problems are met in the designing of achromatic lenses.

Experiment 68

Astronomical Telescope

A single converging lens may be used as a simple microscope or reading glass. The image will be virtual, erect, and magnified, if the object is placed inside the principal focus (Fig. 2, Exp. 67). If the object is far distant the above condition cannot be satisfied. In the astronomical telescope a converging lens, called the object glass or objective, is used to form a real image of the distant object (Fig. 1, Exp. 67) and this image is highly magnified by another converging lens called the eyepiece. Draw a diagram of the instrument, constructing carefully the images.

Construct an Astronomical or Transit Telescope.

Use a long-focus lens for the objective and a short-focus lens for the eyepiece. Find the focal lengths of the two lenses. Place a pin in the principal focus of the objective and then adjust the eyepiece until the virtual images of the pin and landscape are distinctly seen when the eye is held near the eyepiece.

Find the Magnifying Power.

(1) Direct the telescope toward a neighboring building. View the stones directly with one eye and through the telescope with the other at the same time. Superimpose the two images and count the number of stones

viewed directly which occupy the space of one viewed through the telescope.

(2) The magnifying power is the ratio of the angles

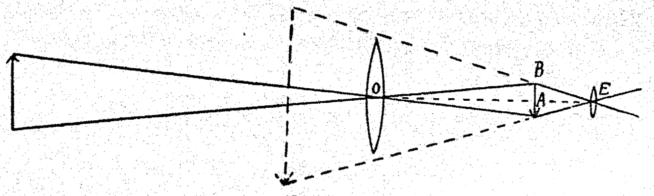


Fig. 1.

subtended at the eye by the image and object respectively, e. g. (Fig. 1)

$$G = \text{angle } AEB/\text{ angle } AOB = \tan AEB/\tan AOB = AO/AE = F/f.$$

The focal lengths of the lenses have been measured. Compute the magnifying power.

(3) An image of the objective is formed by the eyepiece. Hold a screen, shaded if necessary, behind the eyepiece and find this image. Measure the diameter of the image d and of the objective D (Fig. 2). Then, if F and f are the focal lengths of the objective and eyepiece respectively,

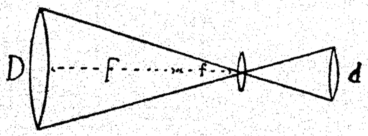


Fig. 2.

$$D/d = (F+f)/v$$

and $1/(F+f)+1/v = 1/f$

whence $(F+f)/v = F/f$

i. e. $D/d = F/f = G.$

Compute D/d, the magnifying power.

Field Glass or Galileo's Telescope.

Remove the eyepiece from the astronomical telescope and replace it with a diverging lens. Move this eyepiece nearer the objective until an erect, magnified image is seen. Where is the eyepiece relative to the principal focus of the objective? Draw a diagram showing the construction of the images within the instrument.

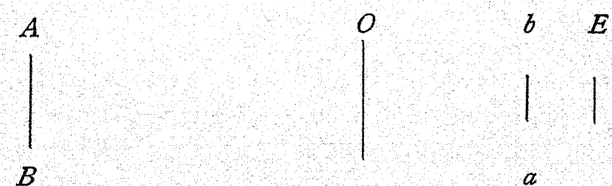
Discussion:—How would you select lenses to make a telescope of high magnifying power?

The diverging eyepiece, used in field and opera glasses, gives a far more compact instrument but it is not adapted for scientific measurements as cross-hairs cannot be used with it.

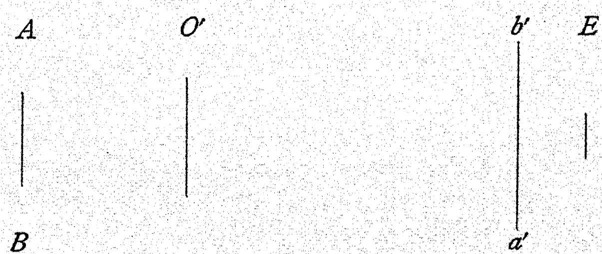
Experiment 69

Compound Microscope

When a real image of an object is formed by a converging lens the sizes of object and image are proportional to their distances from the lens.



Telescope



Microscope

Let O be the objective of a telescope. If the distance of the object AB from the objective is twice that of the image ab, then $ab = \frac{1}{2} AB$. If the distances are interchanged by moving O to O′ the image will again be in the same place (See Exp. 67) but now $a'b' = 2AB$. The eyepiece magni-

fies both images in the same ratio hence the magnifying power of the second instrument is four times that of the first. This illustrates the difference in principle between the telescope and the microscope. To obtain a large ratio between $a'b'$ and AB without making the instrument very long the focal length of the objective is made small.

To illustrate this difference use short-focus lenses for both objective and eyepiece. At a distance from the eyepiece equal to five or six times the focal length of the objective support a meter stick in a horizontal position. Keep the position of the eyepiece fixed throughout the experiment. Place the objective in position and find the two positions in which the image can be distinctly seen. Read the magnifying power in each case (Exp. 68, Method 1). Place a pin on the stand to mark the position of the real image (parallax method), and in later settings always place the image on this pin. Measure the distance of image and object from the objective in each case and see if the above relation between the magnifying powers holds approximately. Illustrate both positions by diagrams of the images constructed to scale.

Move the meter stick toward the eyepiece, following with the objective, until the two images (and the two instruments) merge into one. When the image begins to be blurred or distorted (do not strain the eyes) take the magnifying power. Move the rod back by degrees, following with the objective, and take the magnifying power at several positions until the divisions of the rod can no longer be distinguished. Record in three columns:—

(1) Distance of real image from objective.
(2) Distance of object from objective.
(3) Magnifying power.

The ratio of the above distances gives, in each case, the relative size of the real image and the object. Record this in a fourth column. The magnifying power divided by this ratio, gives the magnifying factor of the eyepiece.

Record this in a fifth column. Is this approximately constant? Notice that, as the magnifying power increases, the object is approaching the principal focus of the objective and the length of the instrument is approaching infinity.

For an instrument of given length how could you select lenses to give a high magnifying power?

Experiment 70

Micrometer Eyepiece

A micrometer eyepiece is an eyepiece containing a cross-hair so mounted upon a frame, moved by a micrometer screw, that it may be placed in coincidence with the image of an object formed by the objective of a telescope or microscope. The hair occupies the position of the pin point in Experiment 69. By means of the micrometer screw the hair may be moved and the distance between two points in the image may be measured. From this the distance between the two corresponding points of the object may be computed.

Examine carefully the construction of the instrument. Focus the eyepiece carefully upon the cross-hairs.

Find the Length Corresponding to One Division of the Micrometer Head.

Focus the microscope upon a standard scale until there is no parallax between the image and the cross-hairs. Place the scale parallel to the line of motion ot the cross-hairs. To do this move the micrometer back and forth, adjusting the scale until a definite point upon the hair follows the edge of the scale. Set the cross-hair in turn upon two millimeter divisions as far apart as convenient and count the number of turns required to move the hair from one division to the other. There is frequently a "comb" or other scale placed in the eyepiece by which the number of whole turns may be counted. Does the pitch of

the screw correspond to the divisions of this scale? In setting the cross-hair eliminate "lost motion" of the screw by always moving the cross-hair into position from the same direction during a given set of readings. Always use corresponding sides of the division marks on the scale. Vary the determination by using the other side of the marks and by setting the hair from the other direction. Find the length on the standard scale which corresponds to one division of the micrometer (1 division = ——mm).

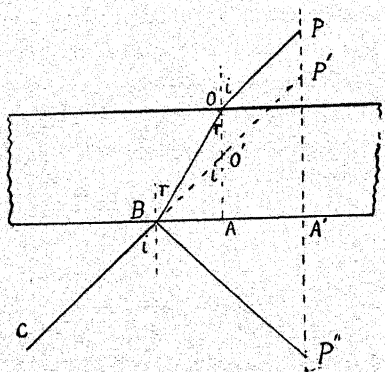
Measure the Two Axes of the Bore of a Thermometer Stem.

Use all precautions outlined above. Assuming the section to be an ellipse compute the area. Area $= \pi ab$ where a and b are the semi-axes of the ellipse.

Experiment 71

Index of Refraction of Glass—Thick Plate

Let a ray of light from P fall upon the glass at O (angle of incidence $= i$). The ray will be refracted along the direction OB (angle of refraction $= r$) and will emerge from the glass in the direction BC, parallel to the original direction. If $\mu =$ the index of refraction we have



$$\mu = \frac{\sin i}{\sin r} = \frac{AB/BO'}{AB/BO} = \frac{BO}{BO'}$$

When the incidence is normal

$$BO/BO' = AO/AO'$$

AO is the thickness of the glass and $AO' = AO - OO'$ where $OO' = PP'$ = the apparent displacement of the object when seen through the glass. This displacement can be found by either of the following methods.

Method 1. A plate ot glass gives two images of an object placed in front of it, one by reflection from each surface. Either of these images may be used but we shall use the nearer one only.

Place a pin at P″. Its image, by reflection at B, is at P′, where $P'A' = P''A'$. Attempt to place another pin in coincidence with this image at P′. A new image is seen at P′ but the pin is really at P, the light having traversed the path POBC to the eye. Now $PP' = A'P - A'P' = A'P - A'P''$. $A'P$ and $A'P''$ can be measured and μ computed from the above formula.

When placing the two images in coincidence tip the glass block until the points of the two images are at the same height. Test for coincidence by the parallax method.

Method 2. Mount a microscope, the focal length of whose objective is greater than the thickness of the block of glass to be used, upon a micrometer screw. Focus the microscope upon a mark on a piece of paper smoothly mounted upon plate glass. When properly focussed the image of the mark coincides with the cross-hairs of the microscope so that there is no parallax between them when the eye is moved from side to side. If there is some range within which no parallax appears move the microscope, first in one direction, then in the other, until parallax can be detected and take the mean of the two readings of the micrometer. Make several independent settings.

Place the block of glass over the mark on the paper. The mark now appears to be at O′, nearer the eye. Focus

the microscope as before and note the reading of the micrometer. The distance the micrometer has moved is equal to OO'. From this AO' can be found and then the index of refraction can be computed.

Experiment 72

Adjustment of a Spectrometer

A spectrometer consists essentially of a telescope for observing and measuring angles, a collimator for rendering the rays of light parallel, and a table upon which a prism or grating may be placed. The telescope and table may be turned about a common vertical axis and angles may be read from a circular scale by means of a vernier attached to the telescope arm. The instrument is used to measure angles for various purposes and it is essential that the rays of light used should remain in a plane perpendicular to the vertical axis.

The collimator and the graduated circle may not be found on the instruments used for practice in adjustment.

When the spectrometer is in adjustment (a) the telescope is focussed for parallel rays with the cross-hairs at the principal focus of the objective, (b) the faces of the prism or grating are parallel to the axis of the instrument, (c) the line of collimation of the telescope is perpendicular to the axis of the instrument, (d) the line of collimation of the collimator is perpendicular to the axis of the instrument, (e) the slit is in the principal focus of the collimator objective.

(1) The set of cross-hairs is placed in the principal focus of the telescope objective as a point of reference. Adjust the position of the cross-hairs or of the eyepiece until the hairs are in distinct focus.

(2) Direct the telescope toward a distant object and

focus until there is no parallax between the image and the cross-hairs.

(3) Place a double faced plane mirror on the platform with its faces parallel to the line between two levelling screws. In subsequent adjustments of the platform always use the third screw.

(4) Direct the telescope toward the mirror and adjust its axis perpendicular to the mirror as nearly as possible with the eye, i. e. the telescope and its image should lie in the same straight line.

(5) Adjust a candle and the glass at the eyepiece (Gaussian eyepiece) to reflect light down the tube until the intersection of the cross-hairs is brightly illuminated. Turn the platform slowly and adjust if necessary until the candle light is reflected back normally into the telescope. Adjust the focus of the telescope if necessary until the cross-hairs and their image can be seen and until there is no parallax between them. Bring the intersections into coincidence. The telescope is now adjusted for parallel rays (Why?) and its line of collimation is perpendicular to the mirror but is not, probably, perpendicular to the central axis. Make drawings to illustrate.

(6) Turn the platform and mirror through 180°. The image no longer coincides with the cross-hairs. Move the image halfway to coincidence by the platform screw and the other half by the telescope screw. Reverse again and repeat, as in the experiment for adjusting a level, until the image remains in position. The axis of the telescope is now perpendicular to the vertical axis of the spectrometer and the faces of the mirror are parallel to this axis. The mirror may now be replaced by the prism or grating to be used and this may be leveled up directly. In doing this do not disturb the adjustment of the telescope.

(7) To adjust the collimator illuminate the slit and turn the telescope directly opposite to the collimator. If the slit can be seen without removing the prism adjust the

focus and position of the collimator directly. If the slit cannot be seen directly use the face of the prism as a mirror to reflect light from the slit into the telescope and adjust as before.

Disturb the adjustments and repeat.

No report upon this experiment need be handed in.

The Gaussian Eyepiece.

The Gaussian eyepiece usually has a plate of plane glass inserted between the lens and the cross-hairs at an angle of 45° to the axis of the tube. Light thrown in at the side of the tube is reflected upon the cross-hairs which may still be seen from the eye end by looking through the glass. When the telescope is perpendicular to a plane reflecting surface an image of the cross-hairs coincides with the hairs themselves, provided they are in the focal plane of the objective. If the instrument does not have a Gaussian eyepiece the cross-hairs may be illuminated by placing a small plate of glass just outside the eyepiece and reflecting the light through the lens.

Sometimes two sets of cross-hairs, with a tiny mirror behind one of them, are placed in the focal plane of the telescope. In this case an image of the illuminated set of hairs is thrown back by a reflecting surface in front of the telescope and this image may be placed in coincidence with the other set. The normal to the reflecting surface then lies halfway between the two sets of cross-hairs.

Experiment 73

Angle of a Prism

Handle the spectrometer with special care. Examine the instrument carefully, noticing the clamps, tangent screws, and other delicate devices. Determine the "least count" of the verniers. If the prism is upon the table test the adjustment before disturbing anything.

If not in adjustment place the prism upon the table with one face perpendicular to a line joining two adjusting screws and with the refracting edge near the center of the table. Adjust the instrument as directed in Experiment 72. The faces of the prism may be used as the double faced mirror.

Measurement of the Angle.

Method 1. By means of the Gaussian eyepiece set the telescope perpendicular to one of the faces of the prism and read the vernier. Without disturbing the prism set the telescope perpendicular to the other face and read the vernier again. The difference in the reading is the supplement of the angle of the prism. Draw a diagram and prove that this is true. Turn the prism table slightly and repeat.

Method 2. Place a light before the slit of the collimator, using a narrow slit. Turn the edge of the prism directly toward the collimator lens so that part of the light will fall upon each face of the prism. Set the cross-hairs of the telescope upon the image of the slit reflected from one face of the prism and read the vernier. Set the cross-hairs upon the image reflected from the other face and read the vernier again. The difference in the readings is twice the angle of the prism. Draw a diagram and prove that this is true. Move the prism table very slightly and repeat.

Experiment 74

Minimum Deviation—Index of Refraction—Prism

Use the prism whose angle you have measured in Experiment 73. Test the adjustment of the spectrometer and adjust if necessary. Illuminate the slit of the collimator and turn the prism so that the light will pass through. If white light is used it will be dispersed by the prism and

the colors of the spectrum will be seen, the deviation being different for the different colors. If the prism is turned the deviation will change and there is one position of the prism for each color at which the deviation is a minimum. Notice that this position is not the same for all colors. The deviation of a ray, when at its minimum, is called the "angle of minimum deviation."

Illuminate the slit with sodium light obtained by holding a piece of glass in a Bunsen flame. The yellow light is deviated but not dispersed by the prism. Set the prism in the position which gives minimum deviation for this ray and set the cross-hairs of the telescope upon the image. Read the vernier. Turn the prism table until the deviation is in the other direction and find the position for minimum deviation on this side. Set the telescope and read the vernier again. The difference in the readings is twice the angle of minimum deviation. Repeat several times.

Find the angle of minimum deviation for the red ray of lithium, or for a ray of some other metal, obtained by holding a bit of some salt of the metal in the flame. Notice that the yellow sodium line is nearly always present and do not confuse it with the line sought.

When the prism is in the position of minimum deviation the angles made by the incident and emergent rays with their respective faces are equal. Verify this by measuring the angles for sodium light. To do this note the position of the emergent ray. By means of the reflected image of the cross-hairs find the normal to this face. These readings give the angle of the emergent ray. Measure, or compute from the last reading, the position of the normal to the other face. To find the position of the incident ray turn the telescope opposite to the collimator and view the slit past the edge of the prism (turned to one side if necessary). This reading, plus or minus 180°, gives the position of the incident ray whence the angle of incidence of this

ray may be found. Are the angles of incidence of the incident and emergent rays equal?

If A is the angle of the prism and D the angle of minimum deviation for a given wave-length of light the index of refraction of the glass for that wave-length is given by

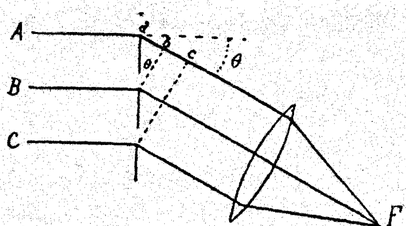
$$\mu = \frac{\sin \frac{1}{2}(A+D)}{\sin \frac{1}{2}A}$$

Compute the indices of refraction of this glass for the rays whose minimum deviations have been measured.

Experiment 75

Diffraction Grating—Wave-Length of Light

A diffraction grating (transmission type) consists of a plate of glass upon which opaque lines are scratched at very small but equal intervals. Ether waves (light) starting together from the slit of the collimator reach the grating in the same time and hence in the same phase. After passing



through the transparent slits the waves pass out in spherical wave surfaces. Some of these fall upon the telescope objective and are brought together at its principal focus. If they are in the same phase at this point they reinforce each other and give light, if in opposite phase they oppose each other (destructive interference) and darkness results. The only difference in phase between the vibrations in the rays A and B is the distance ab. If this is exactly one wave-length A will be reinforced by B, which is one wave-length ahead, by C which is two wave-lengths ahead, etc.

If ab is not an exact wave-length the vibration from A will be opposed by a vibration in opposite phase from some other slit, so for B, and so for all the rest. Thus at the point F there will be only light whose wave-length is ab or some submultiple of ab, i. e. $n\lambda = D \sin \theta$ where D is the distance between two adjacent slits and n is the order of the spectrum. Starting in either direction from the central line, where all waves reinforce, the point F passes through the region of reinforcement of waves too short to affect the eye, then from blue (shortest visible waves) through the spectrum to red (longest visible waves) then again to blue (when ab equals two blue wave-lengths, $n = 2$) and so on.

Examine the spectrometer carefully, noticing the clamps, tangent screws, and other delicate devices. Do not disturb the adjustment until it has been tested. If necessary to adjust use the grating as the double faced mirror and follow the method of Experiment 72.

Illuminate the slit of the collimator with white light and examine the spectra on both sides of the central white line.

Make the slit narrow and illuminate it with sodium light. Measure the angle between the spectral lines of the first order on opposite sides of the central line. This angle is 2θ. Obtain the grating space from an instructor (it may be measured with a microscope or obtained from the maker) and compute the wave-length of sodium light from the formula $\lambda = D \sin \theta$. Measure the angle between the spectral lines of the second order and compute the wave-length again.

Measure the wave-lengths of the principal lines of one or two other substances.

Discussion:—How does the number of lines per centimeter on the grating affect the dispersion? How does it affect the number of orders of spectra visible? How should a grating be designed to give a pure spectrum?

Experiment 76

Solar Spectrum

By means of mirrors reflect a beam of sunlight through the collimator slit and upon the grating. Close the slit enough to bring out the fine vertical lines across the spectrum. These are the Frauenhofer lines.

Set the telescope at the angle found in Experiment 75 for the sodium line. If the slit is very narrow the line will be found to be double. The wave-lengths of the two components are

$$D_1 = 0.00005896 \text{ cms and } D_2 = 0.00005890 \text{ cms.}$$

Set upon each of the lines in turn and, using the wave-length given, determine the grating space.

Set the telescope at the other angles measured in Experiment 75. Which of the materials used are found in the sun? Determine the wave-lengths of these lires accurately. Look through the solar spectrum and measure the wave-lengths of a few of the most prominent lines. Plot these to scale and draw in more roughly other lines which you have not time to measure.

Which of the lines commonly designated by letters (See Appendix) have you located?

Experiment 77

Polarization and Double Refraction

Definition:--Light reflected from glass at an angle of incidence about 57° is plane polarized. The plane of polarization is the plane of incidence.

(1) Arrange the pile of glass plates, using the graduated scale, so that the light from a candle is reflected, at the polarizing angle, along the axis of the instrument. Find the position of a Nicol's prism when the light so reflected is shut out by the Nicol. Call the symmetrical plane through the shortest diagonal of the Nicol the

"principal plane." What is the position of the principal plane relative to the plane of polarization of the light when it emerges from the Nicol? Examine the light transmitted by the pile of plates. In what plane relative to the light reflected is it polarized?

(2) Allow the polarized light to fall upon a second pile of plates whose rotation axis is perpendicular to that of the first pile. Vary the angle of incidence and observe the reflected light. What is the angle of incidence when the reflection is a minimum? Is light transmitted in this position? How is it polarized?

Without changing the angle of incidence rotate the second pile of plates 90° about the axis of the instrument. Is light now transmitted? Reflected? In what plane is it polarized? Can you find a position of minimum reflection? What general conclusions do you draw?

(3) View a dot on a piece of paper, or a letter on a printed page, through a crystal of calcite, the material of which the Nicol is made. Hold the calcite so that its face is parallel to the paper. Observe the motion of the images as the crystal is rotated. Looking down vertically determine which is the "ordinary" and which the "extraordinary" ray. By the method of parallax determine which image is nearer the eye. For which ray is the index of refraction greater (Exp. 71)? Which ray moves through the calcite with the greater velocity? Determine the plane of polarization of each ray relative to the principal plane. When ordinary nonpolarized light falls upon a Nicol which ray passes through? What becomes of the other ray?

(4) View sodium light through two Nicols. Place the principal plane of the polarizer horizontal and shut out the light by rotating the analyzer. Place a quartz plate between the Nicols. Can you again shut out the light by rotating the quartz? By rotating the analyzer? Explain.

Remove the quartz and again cross the Nicols. Insert a piece of mica. Can you shut out the light by rotating the mica? When the light is so cut out can you affect it by rotating the analyzer? Again crossing the Nicols can you bring in the light by rotating the mica? Can you now shut it out by rotating the analyzer? Explain.

APPENDIX

Period of Vibration by the Method of Passages

Two observers are necessary. One counts aloud the passages of the pendulum through the position of equilibrium indicating the tenth, twentieth, thirtieth, etc., passage by a sharp rap with a pencil. The other watches the second hand of an ordinary watch and records the time of the raps as follows:--

No. of Vibr.	Time m	Time s	No. of Vibr.	Time m	Time s	Time of 50 Vibrs. m	Time of 50 Vibrs. s
10	37	14.6	60	39	46.4	2	31.8
20		45.0	70	40	16.8	2	31.8
30	38	15.8	80		47.2	2	31.4
40		45.6	90	41	17.4	2	31.8
50	39	16.0	100		47.8	2	31.8
				Mean		2	31.72

The last column is obtained by subtracting the time of the 10th passage from that of the 60eth, the 20eth from the 70eth, etc. This method gives five independent determinations of the time of 50 vibrations while counting only 100 vibrations. It can obviously be extended indefinitely.

Mechanical Units

1 inch	= 2.540 centimeters.
1 centimeter	= 0.3937 inches.
1 kilometer	= 0.6214 mile.
1 square inch	= 6.451 square centimeters.
1 cubic inch	= 16.386 cubic centimeters.
1 pound	= 453.59 grams.
1 watt	= 10^7 ergs per second.
1 horse-power	= 746 watts.
	= 33000 foot-pounds per minute.

Elastic Constants of Solids

	Coefficient of rigidity	Young's Modulus
Brass	3.7×10^{11}	10.4×10^{11}
Iron (wrought)	7.7×10^{11}	19.6×10^{11}
Steel	8.2×10^{11}	22.0×10^{11}

Densities

Aluminum	2.5 to 2.8	Glass	2.6
Brass	8.4 to 8.7	Air	0.001293
Copper	8.9	Hydrogen	0.000090

Average Coefficients of Linear Expansion Between 0° and 100° C

Brass	0.000018	Iron (soft)	0.000012
Copper	0.000017	Iron (cast)	0.0000105
Glass	0.000009	Steel	0.000011

Average Coefficients of Cubical Expansion Between 0° and 100° C

Mercury	0.00018	Air	0.003665

Specific Heats

Copper	0.093	Brass	0.09

Density of Water at Different Temperatures

Degrees		Degrees	
0C	0.999878	16C	0.999004 9
1	0.999933	17	0.998839
2	0.999972	18	0.998663
3	0.999993	19	0.998475
4	1.000000	20	0.998272
5	0.999992	21	0.998065
6	0.999969	22	0.997849
7	0.999933	23	0.997623
8	0.999882	24	0.997386
9	0.999819	25	0.997140
10	0.999739	26	0.99686
11	0.999650	27	0.99659
12	0.999544	28	0.99632
13	0.999430	29	0.99600
14	0.999297	30	0.99577
15	0.999154	31	0.99547

Vapor Pressure of Water at Different Temperatures

Degrees	Pressures in Centimeters of Mercury	Degrees	Pressures in Centimeters of Mercury
-5C	0.39	98C	70.71
0	0.46	99	73.32
5	0.65	99.2	73.85
10	0.91	99.4	74.38
20	1.74	99.6	74.92
30	3.15	99.8	75.46
40	5.49	100	76.00
50	9.20	100.2	76.55
60	14.89	100.4	77.10
70	23.33	100.6	77.65
80	35.49	100.8	78.30
90	52.55	101	78.77
95	63.34	102	81.61
97	68.19	110	107.54

Barometer Corrections for Temperature

Mercury—Brass Scale Correct at 0 ° C.

Temperature Degrees	73 Cms.	74 Cms.	75 Cms.	76 Cms.	77 Cms.
10C	0.12	0.12	0.12	0.12	0.13
12	0.14	0.15	0.15	0.15	0.15
14	0.17	0.17	0.17	0.17	0.18
16	0.19	0.19	0.20	0.20	0.20
18	0.21	0.22	0.22	0.22	0.23
20	0.24	0.24	0.24	0.25	0.25
22	0.26	0.27	0.27	0.27	0.28
24	0.29	0.29	0.29	0.30	0.30

Electro-chemical Equivalents

Copper (cupric)	0.003261	Oxygen	0.000828
Hydrogen	0.0001035	Silver	0.011180

Wave-Lengths in Centimeters of Frauenhofer Lines

A	0.00007621	b	0.00005184
B	0.00006870	F	0.00004861
C	0.00006563	G	0.00004308
D_1	0.00005896	g	0.00004227
D_2	0.00005890	H	0.00003969
E	0.00005270	K	0.00003934